

EYE MOVEMENT STRATEGIES DURING ATTENTIONAL TRACKING

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To my mother, for supporting me in every endeavor

and

To the Nashville Rollergirls, for providing enough distraction for me to focus

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CHAPTER I

INTRODUCTION

Methods of Selection

Imagine yourself as a police detective in New York City in pursuit of a dangerous criminal. After months of surveillance, you have located the criminal's hideout and are awaiting his return to make your arrest. As you make your approach, however, he spots you and flees the scene quickly, jumping into the nearest taxicab. You attempt to pursue him, but are faced with a challenge. Being that the streets are full of yellow taxicabs, you must pay close attention in order to keep track of which cab contains the criminal. This is a dramatic example of a situation that you might come across while watching television, but it actually highlights an everyday life occurrence: the need to keep track of the people and objects that surround us.

The necessity of tracking arises from the reality that our environments contain more information than we have the ability to process at any given point in time. To deal with the potentially overwhelming amount of information around us, we have developed methods of selection that facilitate our interactions with the world. Typically, we focus on only a small portion of the environment at a time, maximizing the information received from the area and suppressing the information from surrounding objects. The detective chasing the criminal will try to focus on the cab the criminal got into and suppress the nearby people and cars. The ability to focus in this manner is referred to as attention, and it is thought to be the mechanism by which we selectively process items of

interest in our environment (Pashler, 1998). The manner in which we attend can be both overt and covert. An overt indication of attending to something is to direct our gaze such that the fovea, the area of highest visual resolution, is centered on the object of interest. We can attend covertly by directing awareness to something in our periphery without moving our gaze towards this object.

It is often the case, however, that there is a need to focus on more than one item in the environment at a time, and it is this type of situation that I am interested in. Because visual selection is limited to focusing gaze at one location, covert attention is necessary to supplement it so that more can be tracked than what is being looked at. In this way, the allocation of attention and the placement of gaze work together to support efficient processing of the information in a complex scene. The question at hand is what mental processes and environmental factors influence the manner in which eye movements are deployed to best foster the goals of the observer. To illustrate this idea, imagine you are trying to chase a group of three mafia members that all jumped into separate taxis. It is possible that you will move your gaze quickly from one taxi to another to try and monitor their movements. However, you might also choose to fixate at some central location and track the movements of the taxis in your periphery. What determines where you will direct your gaze when you are attempting to monitor several taxis at once? Their speed? Your viewing distance? The location of the most dangerous criminal? It is this sort of situation – where there is a choice about where to focus one’s eyes to better attend to multiple things at once – that the present study will examine.

My previous research suggests that people tend to look toward a central point in between the objects they are tracking, rather than always looking directly at each of them

(Fehd & Seiffert, 2008). I refer to this eye movement strategy as center-viewing and have investigated the nature of it in five experiments. An object-based explanation of this strategy is that people focus their gaze on the center of an invisible object formed in their mind whose vertices are the targets. An alternative explanation is that people look towards the center because it is the balance point of attention that is directed to each of the targets' locations. With the goal of determining whether either of these theoretical explanations of the cognitive processes involved in tracking can account for use of the center-viewing strategy, I have tested which factors contribute to the choice of center-viewing.

Because center-viewing involves the coordination of visual and attentional selection, I discuss both separately and then consider the interplay between them. To orient the reader, the introduction is structured as follows. To begin, I explain how visual selection occurs through movements of gaze. First, the ways in which eye movements are indicative of mental processes are discussed. Then, the use and development of eye movement strategies are presented. I then shift to discuss how attention is used to select information. First, I explain current theories of how attention works when multiple objects need to be attended. Then, the known limitations to attentional tracking of multiple objects are discussed. I then present work involving both visual and attentional selection. First, the previous investigations of eye movements during tracking, in which center-viewing was discovered, are presented. Finally, the theoretical motivations behind each of the experiments exploring center-viewing are explained.

Visual Selection

A window into cognition

As we navigate through the world, we make eye movements to gather information about the surrounding environment. Gaze placement and movement is divided into three categories: saccades, rapid shifts of gaze from one point to another; pursuit, a steady movement of gaze to keep the fovea centered on a moving target; and fixations, stabilizing gaze at one location. While saccades and pursuit may appear to be only reflexive, they can be influenced by, and thereby show signatures of, elements of high-level cognition, including attention, memory, and expectations (Kowler, 1990). The mental planning involved in relatively simple, familiar activities is evident in the eye movements of the person performing the task. Participants making a cup of tea (Land, Mennie, & Rusted, 1999) or a peanut butter and jelly sandwich (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003) saccade to the objects involved with the task (e.g. the kettle or the knife) immediately prior to using them, as if confirming the object's location before moving to the next step. An example of a high-level concept influencing low-level eye movements is shown by evidence of an object permanence effect on pursuit eye movements. These eye movements are used to keep track of a moving target and will typically slow down immediately if the target disappears unnaturally. However, this was not the case if there was an explanation for the disappearance. Pursuit did not slow if the target seemed to be covered by an occluding object, showing an effect of object permanence (Churchland, Chou, & Lisberger, 2003). The strength of the link between eye movements and cognition can be pervasive, as when people are imagining

performing an activity, such as waving their hand back and forth, their eye movements move in the same manner as when they perform the task (Heremans, Helsen, & Feys, 2008). Language experience has also been found to influence eye movement patterns. When viewing a video in preparation of a verbal response indicating what they saw, English and Greek speakers looked at different parts of the same videos depending on the noun/verb structure of their languages (Papafragou, Hulbert, & Trueswell, 2008). These examples indicate that visual selection can be directly tied to the thoughts and intentions of the observer.

Visual selection is also tightly linked with the allocation of spatial attention. There is evidence to suggest that attention is shifted to a location before a saccade is made to it (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). An accurate spatial attention signal is necessary for saccades to be made to peripheral targets amidst distractors. A precise saccade to the center of a group of targets is possible when differently colored distractors are intermixed with the targets (Cohen, Schnitzer, Gersch, Singh, & Kowler, 2007). Here attention is able to segregate the targets from the distractors based on their color difference, allowing the computation of the saccade to be based only on the targets. This sort of saccade is imprecise if made to a single target amidst a group of same-colored distractors, because the target cannot be distinguished from the distractors (McGowan, Kowler, Sharma, & Chubb, 1998). In this case, the saccade often lands near the center of the group formed by the target and the distractors, as if they together formed a spatially extended target. It seems that an accurate saccade can only be planned if attentional filtering occurs, reducing the influence of the distractors. These results suggest that the precision of visual selection can depend on

attentional selection. Disruptions in attentional selection can be triggered by the abrupt onset of a distractor when attempting to focus elsewhere (Yantis & Jonides, 1984). If an abrupt-onset stimulus occurs and captures attention while a saccade is in progress, the trajectory of a saccade will deviate away from the uniquely colored saccade target (Theeuwes, Kramer, Hahn, & Irwin, 1998). Here, despite the fact that the color of the target makes it easily distinguished from the non-onset distractors, the capture of attention by the abrupt-onset causes the saccade to deviate towards the abrupt onset distractor. This phenomenon, called oculomotor capture, occurs even when the distractor is not present, but it is expected to appear by the participant (Van der Stigchel & Theeuwes, 2006). As with saccades to groups of targets amidst distractors of a different color (Cohen et al., 2007), inhibition of the distractors can improve attentional selection if there is advanced notice. Oculomotor capture can actually be overcome if a precue to the saccade target's location is given in advance (Theeuwes et al. 1998). Cuing the target in this way allows attentional selection of the target's location to begin so that the abrupt onset distractor location is already inhibited when it appears. Through these examples, it is possible to see how visual selection is strongly influenced by the allocation of attention.

While visual selection is guided by the intentions, thoughts, and attentional allocation of an observer, it is also possible for visual selection itself to influence cognition and perception. From an illusion where widely separated targets flashed before and after a saccade are perceived to occur in the same place, it is shown that the perception of a target's location is based on the computation of the saccade originally planned and not the one that is made (Bahcall & Kowler, 1999). This is a case where

perception is misguided by the eye movement system. There are compelling examples of the production of eye movements actually triggering insightful problem solving, whether these eye movements were spontaneously produced (Grant & Spivey, 2003) or required of the subject in an unrelated task (Thomas & Lleras, 2007). Notably, participants for the most part were unaware of the relationship between the eye movements they made and their sudden insight into how to solve the problem.

In fact, self-awareness of overt visual selection is not always present even when it seems to be. At the moment that participants detect a hidden figure in an image, the prior 9 fixations indicate that they were actually already looking at the figure as if they did see it (Holm, Eriksson, & Andersson, 2008). Returning to the oculomotor capture phenomenon discussed previously, participants are generally unaware of the abrupt onset distractor if its luminance is equivalent with other items in the display (Theeuwes et al. 1998). If the onset is made more conspicuous, such that all participants are aware of its presence, participants are much more susceptible to oculomotor capture, as they are unable to inhibit the distractor's influence (Kramer, Hahn, Irwin, & Theeuwes, 2000). Interestingly, despite the saccadic deviations made by participants in the oculomotor paradigm, they are typically unaware of making them. These results show that while cognition and visual selection are intertwined to a sizeable extent, this link is not self-evident to the person involved.

This section demonstrated how people use eye movements to select information from their environment. These mechanisms of overt visual selection are guided by a person's thoughts and distribution of attention, often without their awareness. Eye movements can also be actively used as tools for dealing with complex tasks like reading

and playing sports. The use of eye movements as strategies as well as the ways in which they are developed is discussed in the next section.

Strategic use of eye movements

The focus of this section is to demonstrate how eye movements can be used strategically and the ways in which they are developed with experience. Because the term strategy can vary in different contexts, I will take a moment to clarify the intended meaning of strategy in this work. In general a strategy is a plan of action created to achieve a goal. A strategy of eye movements involves a decision about where to direct gaze in order to accomplish a task. When making this decision about where to look, options are considered based on prior experience and/or intuition. This evaluation process need not be elaborate, but it must occur in some manner to distinguish the formulation of a strategy from a reflexive action. Consider a game of basketball. If a spectator's goal is to monitor several players at once, she must decide where to focus her eyes in order to accomplish this goal. A coach who is used to evaluating player formations may choose to look at a central point between them, but a referee used to obtaining detailed information about each player in order to call fouls may direct gaze to specific players one at a time. A novel observer with no basketball experience might have trouble deciding on a strategy and find themselves adjusting their eye movements over time depending on their success in reaching the goal. Thus, an eye movement strategy refers to the choice of gaze placement after a consideration of options that may be updated according to success or failure in reaching the current goal. In this way

strategic placement of gaze can aid an observer in the selection of information that is critical for comprehension of an environment.

As demonstrated in the previous section, eye movements often reflect the intentions of an observer, such as fixating a kettle when making a cup of tea (Land et al., 1999). More complex goals often engender more deliberate eye movements of which participants are aware. Reading is an example of a situation where people move their eyes strategically to achieve a goal, whose success varies with the eye movement strategy chosen. For instance, participants given the task of reading a passage for content typically engage in either a “linear” strategy of reading every line without looking back to prior sentences or a “look-back” strategy where they return to topic phrases repeatedly throughout the passage (Hyona, Lorch, & Kaakinen, 2002; Hyona & Nurminen, 2006; Rayner, 1998). Notably, these readers are aware of the fixation pattern they engage in while reading and those using the look-back strategy do better than linear readers on tests of retention (Hyona & Nurminen, 2006). Strategic use of eye movements can increase the efficiency with which a task is performed. During a simple task of arranging colored blocks to copy a pattern, participants make frequent eye movements back to the pattern as a way of having an external memory store rather than taxing working memory with memorizing the pattern to be copied (Ballard, Hayhoe, Li, & Whitehead, 1992). While these eye movements were not essential to completion of the task, preventing participants from moving their eyes caused them to take about three times as long.

Because selection is based on the relevance of information in a scene, people move their gaze within a scene to select the information that pertains to the task at hand. This was established in 1967 when Yarbus showed that fixation patterns of people

looking at the same painting differed according to what they were asked to remember in the scene. When asked to remember the clothing worn by people in a picture, participants made eye movements concentrated on each of the people in the painting. When charged with remembering the positions of the people and objects in the picture, eye movements were much more diffuse, nearly covering the extent of the scene (Land, 2007). In a more complex task where participants were instructed to either avoid obstacles or approach them, participants habitually fixated the center of objects they approached and the edges of objects they avoided (Rothkopf, Ballard, & Hayhoe, 2007). The object fixations in each task were made with such regularity that looking at the data alone could predict the task condition. Eye movements made during visual search are known to vary according to the distribution of distractors to produce the most efficient search pattern (Greene & Rayner, 2001; Shen, Elahipanah, & Reingold, 2007). If distractors resembling arrows are arranged so that they provide information about the location of the search target, more optimal eye movements are made and the target is located more quickly than when distractors are arranged randomly (Greene & Rayner, 2001). Similarly, Shen and colleagues (2007) had participants search for a target that is a conjunction of a particular color and shape (e.g. a green X) among a lopsided number of distractors (e.g. twice as many green Os as red Xs). Participant's eye movements were biased to search first for the target in the smaller subset of distractors (e.g. fixating only on the Xs).

Part of learning to play a sport can be developing a strategy of where it is best to look as well. Evidence from both cricket and soccer show that eye movement patterns differ between beginner and expert players (Land & McLeod, 2000; Williams & Davids,

1998; Williams, Davids, & Williams, 1999). When a ball is served to a batsman in cricket, he makes an anticipatory saccade to the location where the ball will bounce before it approaches him (Land & McLeod, 2000). More skilled players show shorter latencies on their saccade to the bounce point, suggesting that they are better at determining the trajectory of the ball when it is pitched. In soccer, when determining the direction of an oncoming kick, more skilled players tend to fixate the midsection of the opponent player rather than fixating the legs or ball, as unskilled players do (Williams & Davids, 1998). This difference suggests that the skilled players have developed an eye movement strategy that focuses centrally, relying on their peripheral attention to monitor the movements of the opponents' limbs. When watching more complicated situations that involved everyone on the field, the experts tended to make many more saccades with quicker intermittent fixations throughout the field of play while the novices showed a slower and less comprehensive search pattern (Williams et al., 1999). These examples show that eye movement strategies develop with experience as knowledge about the information most critical for selection is gained.

The way in which this knowledge is gained is by updating strategies of visual selection as errors are made or the state of the world is changed. These adjustments of eye movement patterns help to ensure that relevant information is selected. Participants walking in a virtual environment were not likely to detect a potential collision with other pedestrians who momentarily took on collision courses towards the participant. However, if a participant did notice a potential collision, they altered their eye movements for the duration of the trial and made many more fixations on pedestrians than prior to the detected collision (Jovancevic, Sullivan, & Hayhoe, 2006). This result

suggests that participants altered their eye movement strategy upon realizing that the pedestrians could be important sources of information about a potential collision.

Updates of eye movements after errors can occur quite rapidly. When preparing to catch a ball that is bounced towards them, people will look ahead to the point where the ball will bounce. The accuracy of this saccade to the bounce point will suffer if the ball thrown is changed to a more elastic one, but participants are able to adjust their pursuit of the new ball's dynamic properties within 3 bounces (Hayhoe, Droll, & Mennie, 2007).

These results show how a change in the visual dynamics of an object can quickly alter the locus of visual selection. Thus, updating an eye movement strategy as more information is learned through observation or through errors can ultimately improve its efficiency. It is important to note that an efficient eye movement strategy does not necessarily eliminate errors, however. For instance, because participants have learned to expect traffic signs at intersections when driving, they make many more fixations when they come to intersections than when driving in the middle of a block (Shinoda, Hayhoe, & Shrivastava, 2001). This makes them susceptible to errors, however, as when traffic signs were placed at unexpected places along the roadside, participants were much less likely to notice them. In order to maintain the efficiency of visual selection that an eye movement strategy contributes, it must be updated as knowledge is acquired or the state of the world changes.

Summary

These findings demonstrate that eye movements can be used strategically to select the most relevant information in a scene. A crucial factor in determining what is relevant

in a scene is the current demands of the task at hand. Additionally, experience with a given task can alter the eye movement strategy used as new knowledge is gained through trial and error. The central issue of this investigation is how eye movements are used strategically to help keep track of multiple objects. The factors that guide observers to use a center-viewing strategy when tracking may stem from how much information is required to perform the task. If only the position of each object is needed, gaze may stay in the center as long as each item can be distinguished peripherally, similar to how experienced soccer players look at the center of an opponent's body when anticipating an oncoming pass (Williams & Davids, 1998). However, if more information is required for each item, or if this information is not readily available when gaze is located centrally, as in the block copying task (Ballard et al., 1992), repeated fixations of the tracking items may be made. Learning about the mental processes involved in tracking will therefore shed light on which factors may be crucial in determining where gaze will be directed during tracking. The next section reviews the properties and limitations of attentive tracking of multiple objects.

Tracking Moving Objects

Tracking multiple objects is thought by some to require effortful attention (Tombu & Seiffert, 2008), as well as tap into high-level cognitive mechanisms such as visuospatial working memory (Oksama & Hyona, 2004). Three competing theories of tracking are described in this section and the differences between them concerning the role of attention and perceptual grouping are highlighted. Many studies have discovered elements central to the process of tracking multiple objects, including the limiting factors

that challenge tracking and the types of selection it requires. There are limits on the amount of information that can be selected at once and successful tracking requires that selection be precise. Additionally, disruptions in both the temporal continuity of the tracked targets as well as their object representations cause impairments in tracking performance. These facets of tracking ability are discussed in their relationship to selection.

The experimental paradigm

While keeping track of objects is involved in everyday circumstances like driving, playing team sports, or pursuing criminals in busy cities, it is difficult to re-create these complex situations in a laboratory. One popular method used to tap into attentive tracking is the multiple object tracking (MOT) paradigm introduced by Pylyshyn and Storm (1988). Their experiment consisted of participants viewing a display of several items, a subset of which flashed briefly to indicate that they were the target items to be tracked. All of the items then began to move about the screen and at various times one item was flashed and the participant responded whether the item was a target or not. Because all of the items were identical, the only way for participants to respond accurately was to somehow track the designated targets as they moved about the display. This situation creates a problem for selection not only because many things must be selected at once, but there are also no distinguishing characteristics to aid selection. In order to selectively attend to the target items, each item's location must be constantly updated. Because the demand for selection is so high in this circumstance, combining the efforts of visual selection with attentional selection may be beneficial to tracking.

Theories of tracking

How people are able to successfully track multiple objects at once is still a question of debate. MOT was developed as a test of the FINST hypothesis, which stands for FINGers of INSTantiation (Pylyshyn & Storm, 1988). FINSTs are a way to rapidly classify information in a scene into objects without processing any of the features of those objects. They provide a link between the outside world and its mental representation that is necessary for an individual to determine an action (Pylyshyn, 2000). According to this theory, there are multiple pre-attentive indexes that can be deployed in parallel to provide quick access to the items they point to (Pylyshyn, 1989; Pylyshyn, 2000; Pylyshyn, Burkell, Fisher, Sears, Schmidt, & Trick, 1994). These indexes attach to objects, not their locations, and attention can then access any indexed item (Pylyshyn, 2000). The value in FINSTs is that they provide a way for limited selection of the visual environment to take place without fully encoding any one thing. Thus, this theory suggests that during MOT a visual index is attached to each target, moving with it over time because it is tied to the object and not its location.

An alternative view of how MOT is accomplished is that it involves independent attentional selection of each of the targets. This view, called multi-focal attention, suggests that attention is split up into multiple foci that are allocated simultaneously to the locations occupied by each tracked object and has gathered support from some investigators (Allen, McGeorge, Pearson, & Milne, 2004, 2006; Cavanagh & Alvarez, 2005). According to the multi-focal model, there are multiple streams of attentional selection, each centered on a target. Each stream encodes information about the target

and passes it along to be processed at a higher level. One critical piece of information selected is the target's location, such that shifts in its location can be noted and a control process can be triggered to move the stream to the new location of the target (Cavanagh & Alvarez, 2005). Thus, in multi-focal attention, MOT is performed by actively attending to each target item and using position information to keep each foci of attention devoted to the target it is tracking.

Another potential theory of MOT is that participants group the targets together into one object and attend to that virtual object as a whole (Yantis, 1992). In this scenario the virtual object is formed at the moment the targets are designated, which serve as the vertices. The internal representation of this object is updated continually by comparing it to the present state of the display as the virtual object contorts within it. According to this view, tracking is maintained by dynamically updating the internal object representation of the configuration of the targets, which are made more salient than the distractors by attending to them as a whole. The success of tracking will thus depend on the ease with which the targets can be grouped.

To gather perspective on these theories of MOT, I will describe their similarities and differences in respects to attention and grouping. In the FINST model, the visual indexes are created in parallel pre-attentively. Attention is then able to access any of the indexes, but can only access one at a time. In the multi-focal model, attention is split into independent foci that cover each target, following them as they move. In the object-based grouping theory a single focus of attention is directed to the virtual object formed by the targets. Attention is thus a crucial part of active maintenance of targets in both the multi-focal and grouping theories, but not in the FINST theory. The concept of grouping

refers to the process by which the visual world is organized into components or objects according to basic principles, such as proximity, similarity, common fate, closure, and good continuation (Wertheimer, 2001). Grouping is an essential part of the ability to form a mental representation of an object with the targets as vertices as well as maintain it in the object-based grouping theory of MOT. In contrast, grouping principles are seen as irrelevant in both the tracking mechanisms posited in the FINST and multi-focal theories. The differences in regards to the function of attention and the relevance of grouping within each of these theoretical frameworks can thus be used as a starting point for differentiating between them.

Information limitations

A common idea in the FINST, multi-focal, and grouping theories of tracking is that selection of information is limited. Limited selection means that there are restrictions to the amount of objects that can be tracked simultaneously. The limit of items that can be tracked before performance suffers is, on average, four items (d'Avossa, Shulman, Snyder, & Corbetta, 2006), a number that has also been given as the capacity estimate for visual search (Fisher, 1984) and visual working memory tasks (Sperling, 1960). This limit is not hard-wired, however, as it can depend on visual properties and change with experience. The capacity limit of attentive tracking may be tied to the amount of information about each object that is being maintained (d'Avossa et al., 2006), as the number of objects that can be tracked decreases when a target's unique identity must be tracked as well (Pylyshyn, 2004; Saiki, 2002; Horowitz, Klieger, Fencsik, Yang, Alvarez, & Wolfe, 2007). Tracking performance of young adults is superior to both

children (Trick et al., 2005) and older adults (Sekuler, McLaughlin, & Yotsumoto, 2008; Trick et al., 2005). Those trained to play attention demanding action video games have higher tracking capacity limits than non-gamers (Green & Bavelier, 2006), as well as increased performance in a number of general attention-related tasks (Green & Bavelier, 2003). Expert trackers also show less dual task interference when concurrently tracking and performing a digit categorization task (Allen et al. 2004). Improvements in tracking performance can be seen within participants across 15-20 repetitions of identical trials (Makovski, Vazquez, & Jiang, 2008). These differences in tracking performance across different age groups and levels of experience reflect underlying differences in neural processing. Individual's capacity limits are well predicted by the strength of event-related potentials measured during tracking, which are thought to be a measure of activity in attention-related brain areas (Drew & Vogel, 2008). Examinations employing functional magnetic resonance imaging (fMRI) have found activity in attention-related brain areas when participants were tracking that increases with higher target loads (Culham, Brandt, Cavanagh, Kanwisher, Dale & Tootell, 1998; Culham, Cavanagh, & Kanwisher, 2001; Jovicich, Peters, Koch, Braun, Chang, & Ernst, 2001). In contrast to this result, it has been found that a reduction in attention-related activity occurs with increased exposure to tracking tasks (Tomasi, Ernst, Caparelli, & Chang, 2004). These results, together with the behavioral evidence suggesting that experience mediates tracking performance (Allen et al., 2004; Green & Bavelier, 2003, 2006), indicate that tracking higher numbers of targets does require more resources, but that the amount of resources needed for tracking diminishes with experience. In terms of selection, this work suggests that processing of selected information is refined with practice.

Spatial selection

In addition to limits in the amount of information that can be selected during tracking, there appear to be limits in the precision of the region of selection. A critical part of tracking is the ability to individuate targets for selective processing. This ability is referred to as attentional resolution and it is far coarser than visual acuity, such that, if a tracking display is too small, you will be able to see all the dots moving around but unable to follow the motion of a particular one (Intriligator & Cavanagh, 2001). During tracking, attention is thought to selectively enhance the representations of targets (Sears & Pylyshyn, 2000) and inhibit those of distractors (Pylyshyn, 2006), though this inhibition may be gated by the ease with which targets can be segregated from distractors (Pylyshyn, Haladjian, King, & Reilly, in press). Attentional selection of targets has even been shown to occur when targets are occluded and essentially invisible to participants (Flombaum, Scholl, & Pylyshyn, 2008). Shim, Alvarez, and Jiang (2008) have posited a mechanism where the area of each target is selectively enhanced with an inhibitory surround. In this way, if two targets come close enough to one another that they enter each other's area of inhibitory surround, mutual suppression will occur, causing them to diminish in salience. An alternative to this idea is that there is a resource-limited attentive tracking mechanism that flexibly scales the area of selection according to the size of the tracked item, but with a cost for each additional target (Alvarez & Franconeri, 2007). Tracking targets are thus maintained as long as the focus of attentional selection is precise enough to be able to resolve each of them. If a distractor dot comes into close proximity with a target and comes within the bounds of the attentional focus, it may

be confused with the target dot. The negative impact on tracking performance seen when the proximity of the dots is increased illustrates the need for a precise window of attentional selection (Alvarez & Franconeri, 2007; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008; Shim et al., 2008; Tombu & Seiffert, 2008). The precision of selection improves when spread across space, as people are capable of tracking more items if they are distributed across different depth planes (Viswanathan & Mingolla, 2002) or across different visual hemifields (Alvarez & Cavanagh, 2005). These results indicate that the ability to track relies heavily on the spatial precision with which attentional selection occurs.

Temporal continuity

In addition to the importance of spatial resolution in selection, a crucial part of maintaining selection of targets during tracking is continually updating their positions. Tracking can thus be adversely affected by disruptions in the temporal continuity of targets, making this updating difficult. If a blank is introduced at some point during the tracking interval such that all dots disappear, participants have a more difficult time recovering targets after the blank if they have continued to move during the blank than if they reappeared in the same location (Keane & Pylyshyn, 2006). This advantage seen when items did not move after the disappearance does not mean that motion information can not be used to help determine the position of targets that move during a blank, as shown by Fencsik, Klieger, and Horowitz (2007), but that location information may be used more readily than motion information in tracking. In addition, some believe that the ability to track across the blanks relies on temporary storage of the information required

to recover targets afterwards (Horowitz, Birnkrant, Fencsik, Tran, & Wolfe, 2006). The continuity of motion information may also be important for keeping attention directed to the location of each target. Verstraten, Cavanagh, and Labianca (2000) found that when subjects were tracking a single bar of a rotating radial grating, they could not reliably track beyond speeds of ~4-8 Hz, despite the fact that motion was still detectable at faster speeds. It seems that an important factor for determining this speed limit, however, was the length of the blank between successive frames of motion. Participants are capable of tracking at faster speeds when blanks are present, presumably because the blank helps attention to disengage from the attended location in preparation to shift to the new one (Benjamins, Hooge, van der Smagt, & Verstraten, 2007). These results indicate that maintaining attentional selection depends upon the continuity of the motion over time.

Object representations

Another important component of selection during tracking is the representation of the selected objects. The ability to track is impaired when the nature of the target objects are altered so that they disappear un-naturally behind an occluder (Scholl & Pylyshyn, 1999) or move from one location to the next as a liquid would rather than a solid (van Marle & Scholl, 2003). The impairment in tracking seen when the object representation is tampered with suggests that there are multiple object representations being tracked and not only their locations. Further it is difficult to attend to only one part of an object, i.e. the end of one line (Scholl, Pylyshyn, & Feldman, 2001), suggesting that attention is not only devoted to the object, but spreads to encompass all parts of an object. This idea is supported by the finding that larger behavioral costs exist when switching attention

between objects rather than within the same object (Egly, Driver, & Rafal, 1994). While this research suggests that attention directed to an object covers the extent of the item (Egly et al. 1994; Scholl et al., 2001), there is also evidence using probe detection to show that attention directed to objects tends to be stronger at the center than at the edges (Alvarez & Scholl, 2005). The effect of attentional concentration at the center is present even when fixation is required of subjects during tracking (Doran, Hoffman, & Scholl, in press), but can be extinguished by eliminating the uncertainty of where the probe to be detected will appear (Feria, 2008).

Summary

To summarize, the amount of targets that can be selected is limited, though tracking ability varies across participants and with experience. Maintenance of selection depends on the precision with which items can be individuated, their motion continuity, as well as strength of their object representations. This section described three theories of how multiple objects can be selected simultaneously. The FINST hypothesis suggests that multiple pre-attentive visual indexes tag each of the targets so that attention can then access them one at a time. The multi-focal and object-based grouping theories pose that attention is actively involved in keeping track of multiple objects. In the multi-focal case attention is split to cover each individual target while in the object-based account attention is directed to the targets as a whole upon completing a perceptual grouping process to form a virtual object. Given these theoretical explanations of tracking, implications for the strategic combination of visual and attentional selection are discussed in the following section.

Eye Movements During Tracking

The main topic of this study is that selection of multiple objects requires both attentional and visual selection, as gaze can only be focused at one location at a time. It is not necessary to move one's eyes to attend to items moving in the periphery (Verstraten, Hooge, Culham, & Van Wezel, 2001), yet eye movements made during tracking are of interest because they may reveal common strategies that lead to successful tracking. More importantly, examining eye movement strategies during tracking may help to distinguish between competing theories of tracking. The primary theories that are investigated in this study are that tracking relies on grouping the targets into a single object or that attention is allocated separately to each target. Before explaining in depth how these two theories account for center-viewing I will review the limited amount of research investigating eye movements during tracking.

Initial investigations of center-viewing

While research on multiple object tracking has now spanned over 20 years, the eye movements made during tracking have only been investigated in recent years. Landry, Sheridan, and Yufik (2001) conducted an experiment using a tracking task that simulated air-traffic control where participants tracked several objects while monitoring for collisions between them. They found that more eye movements were made between targets of a potential collision than to other targets that were not in danger. Another study employing a dual task where participants tracked multiple lines of different lengths as well as detect probes presented in the display also found that the targets were the most

viewed items (Doran et al., in press). These results suggest that looking at targets during tracking helps participants keep track of them, especially when they must be monitored for potential collisions or probes. I refer to the preferential viewing of targets during tracking as target-viewing and it is in contrast with the center-viewing strategy I have found to dominate tracking under single task situations.

My initial examination of the patterns of eye movements made during MOT sought to determine if they would be more consistent with either the visual index or multi-focal theories of tracking. A strategy of saccading from target to target was thought to be more consistent with the visual index theory of tracking, as the theory describes that attention is serially allocated to them one at a time (Pylyshyn, 1989), which

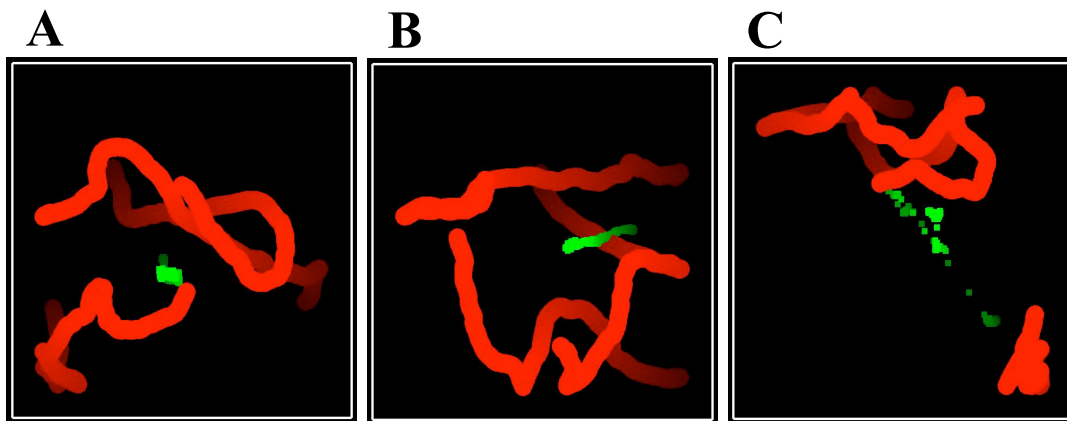


Figure 1. Traces of target and gaze position during trials from Fehd & Seiffert (2008). The trajectories of both the targets (red dots) and gaze (green squares) are shown in example 3-target trials. Timecourse of the trial is represented by the brightening of the color trace. Typically gaze followed a pattern of either (A) staying in roughly the same place throughout the trials, (B) pursuing the general motion of the targets, or (C) saccading rapidly between targets.

might drive eye movements to do the same. A strategy of focusing the eyes centrally was thought to be consistent with either the multi-focal or grouping theories of tracking, because gaze would not be biased towards any one target if attention were directed to all the targets, whether separately or as a whole. I discovered that when tracking 3 out of 8 total dots, participants' eye movements followed three general patterns (Fehd & Seiffert, 2008). First, there were trials in which the eyes stayed in approximately the same place during tracking (Figure 1A). Second, there were trials in which the eyes seemed to pursue the overall motion of the three targets (Figure 1B). Finally, there were trials in which the eyes tended to saccade from the vicinity of one target to another (Figure 1C). The tendency to follow one of the above patterns was quantified by comparing the position of eye gaze to the position of each dot. This was done both by determining the proportion of time that gaze was within a certain distance from each dot and by conducting a location competition analysis where the proximity of each dot to gaze during the trial was weighted to determine which dot was the winner. Both methods revealed the same results. Participants predominantly engaged in a strategy where they tended to look towards the center of the shape formed by the tracking targets rather than at each individual target. The relative amounts that the center and the targets won the competition analysis in the 3-target trials are shown in Figure 2. This center-viewing tendency has also been found in 3D displays, though there was a reduction in its use as the numbers of targets increased from 3 to 5 (Zelinsky & Neider, 2008). This difference across target numbers may be related to the definition of the center they employed, however. We used the center of object, or centroid, to define the center, while they calculated the center by averaging the coordinates of the targets. The center of an object

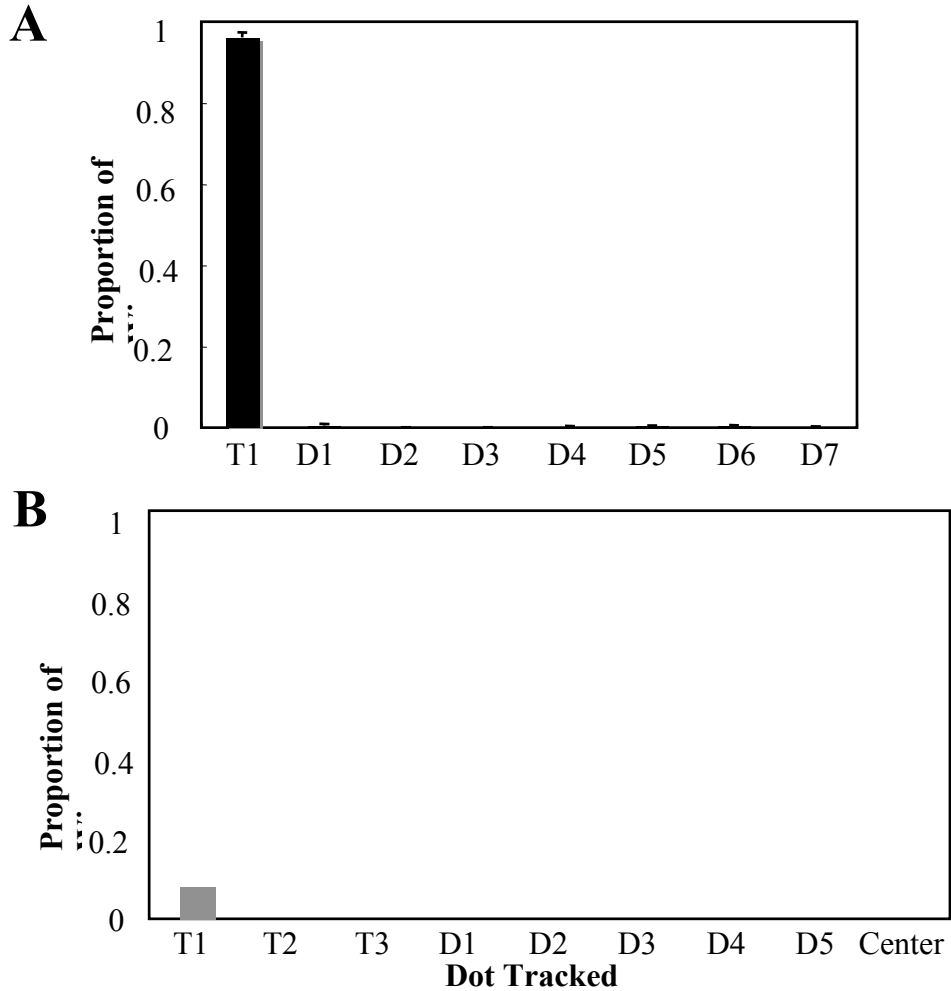


Figure 2. Gaze analysis results from Fehd & Seiffert (2008). Proportion of wins in competitive analysis for each dot (T=target, D=distractor) in 1-target trials (A) as well as the center in 3-target trials (B).

and the average of the vertices' coordinates are the same for three points, but differ with higher numbers of vertices. Using the center of the object as the definition for the center, I found consistent center-viewing across 3, 4, and 5 targets (Fehd & Seiffert, 2008).

One initial interpretation of center-viewing is that participants might look toward a point in the center of the target array in an attempt to minimize the eccentricity of each of the targets. This is likely to help tracking because visual acuity limitations make it more difficult to discriminate items that are close together in the periphery (Yap, Levi, & Klein, 1989). In addition, the ability to individuate two nearby items falls off steeply with eccentricity (Intriligator & Cavanagh, 2001). Thus, attempting to reduce the eccentricity of targets should aid in tracking them. To determine if this was the case, I examined the proximity of gaze to the center and to points that would minimize target eccentricities. I compared the center to two different points of minimum eccentricity, one that would minimize the maximum eccentricity of any one target and one that would minimize the average eccentricity of all the targets. I specifically looked at the moments when the arrangement of the targets caused these eccentricity-minimizing points to be separated from the center by more than one degree. I found that the point of gaze was closer on average to the center than to both of the points that minimized eccentricity. This evidence indicates that participants do not engage center-viewing during tracking solely because they are attempting to reduce target eccentricities. We interpreted these results to mean that people view the center of the target array either because it is the balance point between the foci of attention directed to each of the targets or because it is the center of the object formed by the targets.

Investigating the distribution of attention while center-viewing

Because visual selection is often associated with attentional selection (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), I have investigated whether or not

directing attention to the center is a part of the center-viewing strategy. From a view of multi-focal attention, where attention is divided and discretely allocated to each object (Cavanagh & Alvarez, 2005), it follows that attending to the center of the target array in addition to the targets will decrease the amount of attention available for each target. However, it is possible that participants may attend to the targets as if they formed an object and, concomitant with that, they devote attention to the center of that attended virtual object. Evidence to support this possibility comes from the finding that participants tend to concentrate their attention at the center of objects to which they are attending (Alvarez & Scholl, 2005). To determine if the center is attended during tracking, I used a probe detection task in addition to the MOT task to measure the distribution of attention. I found that participants were better at detecting a brief flash when it was presented atop a target or at the center than when atop a distractor. However, these results do not clearly indicate if attention was directed to the targets' center because enhanced detection at the center was confounded with the propensity for gaze to also be directed there. Notably, these results differ from that of Doran and colleagues (Doran et al., in press) who found that when performing the dual task of MOT and probe detection, targets were viewed more than the center. This difference may be a result of their tracking stimuli, which were lines of varying lengths. It is possible that this sort of target shape is more difficult to track and requires more fixations to distinguish targets from distractors. These experiments neither supports nor refutes the idea that the center-viewing strategy during multiple object tracking is related to attention being directed to the center.

An additional method to test whether or not the center was attended during tracking was to test the effect of placing a distractor dot at its location. Because successful tracking relies on the ability to keep distractors distinct from the targets that are being tracked, looking at distractor dots while tracking might be a hindrance. Placing a dot at the center created a situation where the center could have become a non-ideal place to look. This was not the case, however, as participants looked at the center even more when a distracting dot was shown at its location than when there was blank space at that location. The center was viewed the most when a target dot was shown in its place. The addition of the center dot as a target did not cause the performance decrement that usually follows an increase in target load. In other words, the accuracy for tracking 3 targets was the same as tracking 4 targets if one of them was the center. It may be that participants picked up on the relationship of the dots and found that keeping their eyes at the center dot helped to keep track of the dots that were related to it, whether or not it served as a target or distractor. This argument gains strength when noting that the most tracking errors came from the condition in which the distractors' center was an additional target. Picking up on its relationship with the distractors may have ultimately made it harder to keep track of the target dots that were unassociated with it. Tying the results of these experiments together, it is evident that the center is viewed frequently, but it is unclear whether people attend to this location as they look at it.

Taking into consideration the work examining eye movements during tracking, a few points stand out. First, looking at targets is useful during tracking and might be more necessary as more information about a target is needed than its location. The most common viewing pattern during tracking, however, is not looking from one target to

another, or target-viewing, but center-viewing, where gaze is primarily located near the center of the target array. The tendency to center-view cannot be explained as developing from a goal of minimizing the target eccentricities. Additionally, it is unclear whether center-viewing involves attending to the center location in addition to the tracking targets. Given these findings, two potential theories that might account for the propensity to engage in center-viewing are presented.

Theoretical interpretations

One possible explanation of center-viewing is that participants focus their gaze at the center because they are attending to all the targets as a single shape. Previous investigations of multiple object tracking have shown that tracking performance is improved when participants employed the strategy of mentally grouping the multiple targets into a single polygon and tracking the contorting “virtual” object as a whole (Yantis, 1992). Perhaps if people conceive of the targets as forming an object, then they may look at the center of the object formed by the targets. Evidence showing the importance of the center of an object comes from the finding that when people make saccades to peripheral objects, their gaze tends to land in the center of the object to which they saccade (Kowler, 1995; Vishwanath & Kowler, 2003). If tracking is accomplished by grouping the targets into a single shape that is tracked as it contorts, the center-viewing eye movement strategy can possibly be explained by saying that participants keep their gaze at the center of this virtual object. According to this object-based theory, gazing at the center of the object formed by the target helps to reinforce the mental representation of the object and its vertices, the tracking targets. Notably, in this theory,

the representations of the target locations are not as fragile because the grouping of the targets into a single object spreads attention to the entire object and fosters the representations of each target.

Alternatively, if tracking is achieved by directing separate attentional foci to each target's location, gaze may be directed to the balance point between these foci according to the attentional weight given to each one. If we assume that participants attend to each target equally, the idea of gaze as the balance point of attention could potentially explain the use of a center-viewing strategy. It is important, however, to note that this theory is space-based and relies on the participant's ability to maintain the location representation of each peripheral target so that attention can be directed to them. This location representation could be difficult to maintain for a number of reasons. A distractor entering a foci's location could become confused with the target already inside the foci. Or, if a saccade is made during tracking, target identification will require a location comparison of the targets before and after the saccadic suppression of the visual scene that occurs during an eye movement. It may also be challenging to attend separately to the target locations if there is not enough information available about each item to be able to locate them in the periphery.

Specific aims

As a beginning point for exploring the center-viewing strategy, consider for a moment what is involved in performing the task. After being told the instructions and shown an example trial, participants must reflect on their prior knowledge and expectations about the task and form a plan of action for achieving the goal of

successfully tracking all of the targets. Determining an initial eye movement strategy will involve incorporating prior knowledge about tracking (e.g. sports or action video game experience) and formulation of a motor plan for directing gaze so that the information crucial for tracking is selected. When tracking begins and the chosen strategy is implemented, updated perceptual analysis of the tracking display will be necessary to determine where to direct gaze and if strategy alterations are needed. One critical question about the underlying mechanisms behind center-viewing concerns which perceptual aspects of the tracked items cannot be sufficiently accessed with attentional selection and require visual selection. Another question regards how the goal of tracking is reflected in the choice to view the center. I explored these questions in an attempt to probe the nature of center-viewing.

To better understand what factors contribute to the use of center-viewing, I conducted the following experiments. The aim of Experiment 1 was to determine whether the ease of looking from target to target would affect the use of center-viewing by varying the speed of the tracking items. If center-viewing is a result of eye movement avoidance in order to maintain location representations, the amount of center-viewing should decrease as targets move more slowly. Alternatively, if center-viewing is based on grouping the targets into a single virtual object, center-viewing should persist across variations in speed. In Experiment 2 I determined how center-viewing changed when foveal vision was required to distinguish the targets. If center-viewing is reliant on the ability to gain information from targets when they are in the periphery, it should stop when targets are too small to resolve in the periphery. However, if center-viewing still persists to a degree amidst increased target-viewing, it will support the object-based

theory behind center-viewing. In Experiment 3, I altered the goal of the tracking task in order to explore the top-down components of center-viewing by designating one target to be more valuable than the others. If participants continued to view the center when the targets were unequal in value, it would give further support to the object-based nature of the strategy. However, if participants moved their gaze towards the more valuable targets, it would suggest that center-viewing results from viewing the balance point of the attentional weight given to each of the targets. I tested the object-based grouping hypothesis more directly in Experiment 4 by varying the ease with which targets could be grouped together. If center-viewing is based on object-based attention to the target group, it should vary as the redundancy of target motion is manipulated. Finally, in Experiment 5, I tested the efficacy of center-viewing by determining whether center-viewing resulted in superior tracking performance than the target-viewing strategy. Better performance when center-viewing would imply that this strategy is advantageous for tracking and not simply a common habit of participants. The following chapters reveal the results of these experiments and in the final chapter I will discuss what I have learned about the center-viewing strategy and its usefulness for tracking.

The overall goal of this work is to investigate how people select information from their environments by using both eye movements and attention. The explorations of center-viewing I have conducted add to this knowledge by revealing the properties in a visual scene that guide visual selection when attention is simultaneously devoted to multiple objects. Further, these results will help to determine the effectiveness of combining the efforts of visual and attentional selection in a manner such as center-viewing.

CHAPTER II

EXPERIMENT 1: EFFECT OF SPEED ON CENTER-VIEWING

Introduction

Two alternative theories of attentive tracking are a space-based multi-focal account and an object-based grouping account. In a space-based multi-focal theory, each item is maintained by keeping an attentional focus directed to the updated representation of the location it occupies. Experiment 1 examined whether the difficulty of viewing targets is a factor governing the use of center-viewing. It is possible that the reason center-viewing has been found to be the predominant strategy is that the targets move too fast to make target-viewing a worthwhile strategy. When a saccade is made during tracking not only will visual information be suppressed during the eye movement, but the retinal coordinates of all the dots will also change when gaze arrives at the new location. Such shifts are known to adversely affect tracking (Seiffert, 2005). The problem that arises is that after a shift of gaze all of the dots must be compared to their previously known locations to update each target's location. This is similar to the disruption to motion continuity that occurs when a blank is introduced during tracking (Fencsik et al., 2007; Horowitz et al., 2006; Keane & Pylyshyn, 2006). If the dots are moving at fast speeds, the distance that a target moves during an eye movement may be too great for the target's location to be accurately updated. If the speed of the dots in the display is reduced, more eye movements may be made because the danger of losing one target while looking at another one will be reduced. Center-viewing may actually be a less

effective strategy for tracking, but is used as the default when the cost of making saccades to targets is too high. If center-viewing is a result of avoiding costly saccades to targets, then there will be less overall center-viewing on trials where the dots move slowly. However, in contrast to this space-based multi-focal account, an object-based theory of attentive tracking suggests that tracking is accomplished by grouping the targets into a single virtual object that is tracked as a whole. If center-viewing is a result of grouping the targets into a single object, the quantity of center-viewing should not change across different dot speeds. The results of this experiment test the effect that the speed of the dots had on whether participants primarily viewed the targets center of the target array during tracking.

Methods

Participants

Thirteen people (5 females; aged 18-22) from Vanderbilt University participated in this experiment following the procedures for the protection of human participants defined in the APA Code of Ethics (2002). One participants' data were excluded from the final analysis due to a lack of sufficient eye movement data being acquired because of signal loss by the eye tracking equipment (see Results).

Apparatus

Eye movements were monitored using an Applied Systems Laboratory EYE-TRAC 6000 (ASL, Bedford, MA, USA) running at 120 Hz. Participants used a chinrest

and headrest to sit 38.5 cm from the computer monitor. Stimuli were created with Matlab for OS X and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997). The visual display was generated by a Macintosh eMac driving a Sony Trinitron Multiscan E540 monitor.

Stimuli

Stimuli were 10 red dots (2.1°) presented within a white rectangular frame ($39.8^\circ \times 39.8^\circ$) on a black background. Green rings, 2.9° in diameter, were used to designate targets. Randomized starting positions prevented dots from overlapping with each other or the bordering frame. Each dot moved in a random Brownian-like motion constrained so that each one moves on average a certain number of pixels per frame. Five dot speeds were tested, with the dots moving .5 ($\sim 3^\circ/s$), 1 ($\sim 6^\circ/s$), 2 ($\sim 12^\circ/s$), 3 ($\sim 18^\circ/s$), or 4 ($\sim 24^\circ/s$) pixels per frame. This range of speeds is similar to that of previous studies investigating speed changes in MOT (Alvarez & Franconeri, 2007; Liu, Austen, Booth, Fisher, Argue, Rempel, et al., 2005) and was intended to cover a wide range of performance accuracy.

Procedure

Participants completed one 60-minute session containing 120 experimental and 5 practice trials. At the beginning of the session and after every block of 15 trials, the eyetracking system was calibrated using a 17-point calibration. Five speed conditions were tested: $3^\circ/s$, $6^\circ/s$, $12^\circ/s$, $18^\circ/s$, and $24^\circ/s$. Each trial began with green rings designating 4 of the dots as targets for 3 s. After a 5 s period of motion participants

selected each of the tracking targets with the computer mouse. A high or low tone provided feedback for each correct and incorrect selection, respectively.

Results

Because the center of the tracking targets is only meaningful if the participant is tracking all of the targets, accuracy was defined as the percentage of total trials in which all targets were correctly identified, a measure with a chance level of 0.48% (1 correct out of 210 possibilities of choosing 4 of the 10 dots). The average percent correct across all speed conditions was 58%. An ANOVA on the accuracy data showed a significant main effect of Speed ($F(4,44)=119.68, p<.01$), with accuracies ranging from 13% for the highest speed to 95% for the slowest speed. Correct trials were selected for eye movement analysis if less than 10% of the eye movement data was lost due to errors with the equipment, calibration, or participants' motion (such as blinks or head motion). Data from one participant were removed because their number of excluded trials exceeded 30%. The average number of excluded trials for the rest of the participants was 6.3%.

Data analysis methods

The eye position coordinates were recorded for every frame of the visual display. The data was converted from the arbitrary units of the eyetracker output to the pixel coordinates of the Matlab display by using the calibration points as a reference frame. When combining the locations of dots during trials with the collected eye data, a lag of 3 frames (~25 ms) was incorporated to account for the processing time of the eyetracking software. Only correct trials were used for gaze analysis. The location of gaze was

assessed by conducting a location competition analysis. The purpose of this analysis is to determine where gaze was located in relation to the targets, distractors, and the center. In this procedure, all of the 10 dots and the center were considered competitors. Each competitor was assigned a weight of zero at the beginning of the trial, and weights were then adjusted after each frame such that the competitor closest to gaze received an increase in its weight by 10 while the remaining 10 competitors received a decrease in weight of 1. The competitor with the highest weight value on a given frame was considered the winner for that frame. Summing the total time that each competitor won across all frames and averaging across trials, I measured the average percentage of time that gaze was directed towards each dot and the center. The advantage of this analysis is that accumulating weights provide a history that is resistant to frame-to-frame noise in the data. An additional analysis employed to determine the position of gaze amongst the tracking display is referred to as the window method. This analysis does not take into consideration the frame-to-frame variation of eye position and simply measures the amount of time that the eye position overlaps with a window twice the diameter of the dots ($\sim 5^\circ$). In instances when gaze overlapped with more than one window, the frame counted to the total time viewed for both of them. The number of frames of overlap was summed for each dot and the center and divided by the total number of frames. This percentage of overlap was then averaged across targets and distractors for each trial and subject.

Gaze analysis

Gaze was analyzed to see if viewing time varied as a factor of the type of dot, a target, distractor, or the center, or as a factor of the different speeds that the dots moved at. An ANOVA on the competitive analysis data showed a significant main effect of dot type ($F(2,16)=137.20$, $p<.01$) and speed ($F(4,32)=6.16$, $p<.01$), as well as a significant interaction between the two factors ($F(8,64)=5.65$, $p<.01$). As in my previous work, the center won the location competition much more (44.9%) than the targets (8.9%) or distractors (3.2%). Simple effects ANOVAs revealed a significant effect of speed for the center ($F(4,32)=5.94$, $p<.01$) and distractors ($F(4,32)=3.80$, $p<.05$), but only a marginally significant effect for the targets ($F(4,32)=2.14$, $p=.09$). The percentage of time won increased with increasing speeds for the center (from 31% to 61%) but decreased for the targets (from 11% to 6%) and distractors (from 4% to 2%). These results can be seen in Figure 3A where there is a clear increase in the amount the center won as speed increased, while the target and distractor averages decrease below.

Gaze was additionally analyzed by calculating the amount of overlap between eye position and a window surrounding each competitor. While this analysis has yielded similar results with the location competition analysis in our previous work, these data show a different pattern (Figure 3B). An ANOVA of the window analysis shows only a significant main effect of dot type ($F(2,16)=86.59$, $p<.01$). When analyzed with the window method, the center no longer shows an increase in the percentage of overlap as speed increases ($F(4,32)=0.38$, $p=.82$) and the decrease in overlap time with the targets is only marginally significant ($F(4,32)=2.49$, $p=.06$). A deeper look into the differences between the window and the location competition analysis revealed that the two analyses

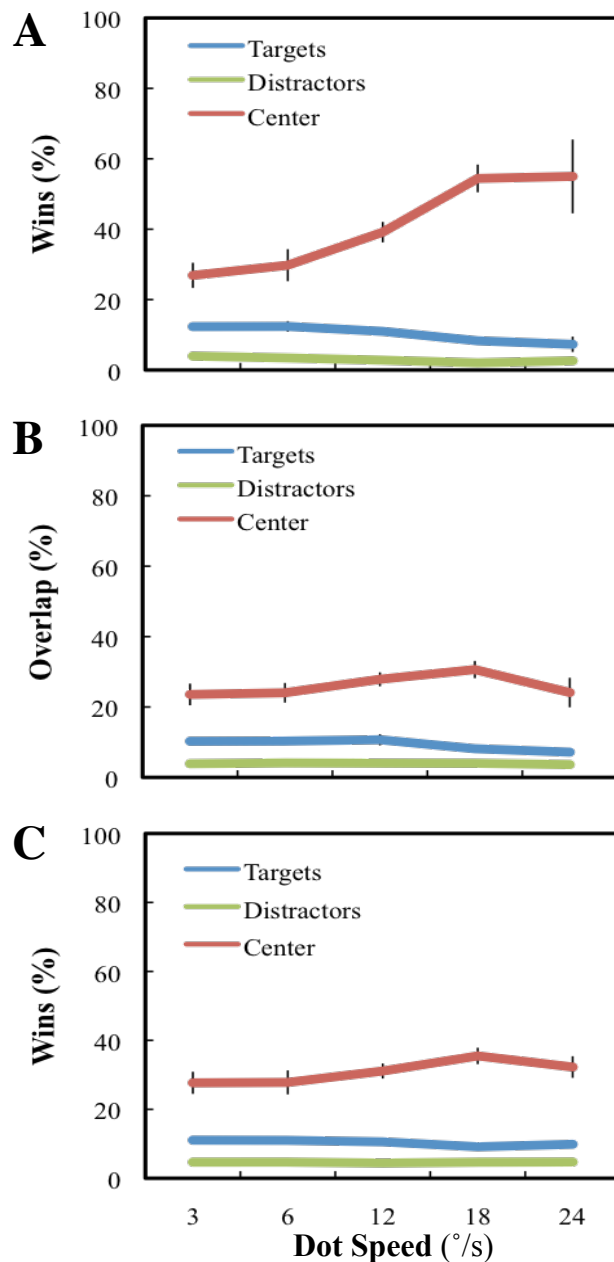


Figure 3: Experiment 1 - Gaze analysis results. (A) Average time that the targets (blue), distractors (green), or the center (red) won the location competition analysis. (B) Average percentage of time that the targets, distractors, or center overlapped with gaze as calculated by the window analysis. Colors are the same as in A. (C) Results from the location competition analysis with the weighting scheme removed. Colors are the same as in A.

produced varying results because of the use of the weighting system in the location competition analysis. The weights accumulate across a trial so that a competitor that has

had several consecutive wins will have a substantially higher weight than a competitor that has had an equal number of non-consecutive wins. This weighting scheme gives the analysis hysteresis so that gaze must be nearest to a competitor for a sizable duration in order to overtake the lead from another competitor that currently holds the lead. To confirm this, I re-ran the location competition analysis using only the shortest distance from gaze to determine each frame's winner, rather than the highest weight. The results show a similar pattern to that of the window analysis, with very little variation in the percentage of center winning across the range of speeds (Figure 3C). The combination of the location competition analysis and the window analysis thus suggest that the overall amount that the center is viewed does not increase with target speed, but, rather, that the duration of each fixation at the center does change. This was confirmed by looking at the average duration of each fixation (Figure 4A), which decreased significantly as the speed of dots increased ($F(3,30)=9.72, p<.01$). In this analysis, the duration of a fixation referred to the number of consecutive frames a competitor was the closest to gaze. I also examined the overall number of fixation alternations, or switches from one competitor to the next (Figure 4B). There was a slight, but insignificant, increase in the number of alternations from one fixation to the next ($F(3,30)=2.11, p=.12$). Further, looking at the beginning and ending points of each fixation alternation, it can be seen that there were overall all more switches between the center and a target than between targets (7.4 vs. 4.5; $F(1,10)=28.94, p<.01$). These data indicate that center-viewing persisted across the varying speeds tested, with the only change in eye movement patterns being a decrease in the amount of time spent at each fixation as the speed of the dots increased.

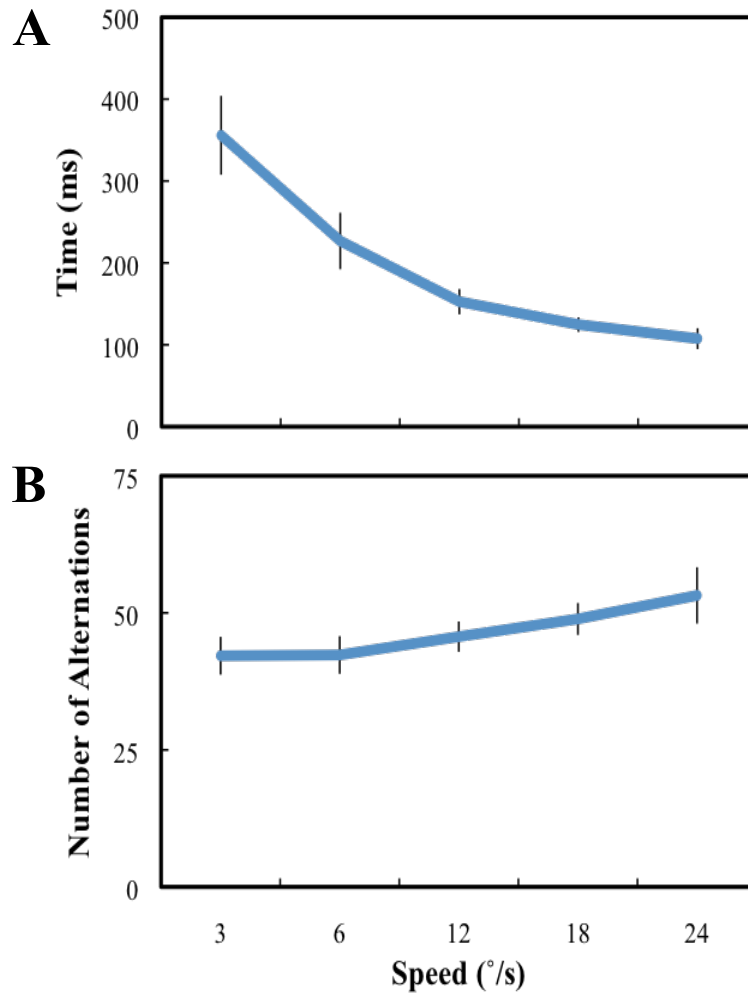


Figure 4: Experiment 1 – Analysis of gaze alternations.
 (A) Average duration of each fixation for each speed tested.
 (B) Raw number of fixation alternations between any of the competitors (targets, distractors, or the center).

Discussion

The objective of this experiment was to establish if the difficulty of viewing targets is a reason behind why people choose to view the center when tracking multiple objects. I found that, despite the variety of speeds tested, there was still a strong tendency for observers to engage in center-viewing. The overall amount of time that

gaze was at the center did not change as speed increased, but the duration of each center fixation decreased. At the slower speeds, participants viewed the center for prolonged periods of time, while at higher speeds they made quick glances to the center. Notably, as the speed of the dots increased there was also a slight increase in the number of gaze alternations made, the majority of which were to or from the center. This increase in costly eye movements is not predicted by the space-based theory of tracking in which foveating the targets is the best use of time because it is necessary to maintain robust location representations of the targets. Rather, these results are consistent with an object-based theory of tracking that posits that center-viewing is caused by grouping the targets to form a virtual object. This theory predicts center-viewing should not change depending on the speed of those targets.

In terms of selection, it is important to note that the targets are never completely abandoned in favor of the center. In fact, at the highest dot speeds – when the price of eye movements was steepest – there were more shifts of gaze between the center and targets. These results suggest that the speed of tracked objects is an important factor for determining when direct visual selection of target information is necessary.

CHAPTER III

EXPERIMENT 2: EFFECT OF TARGET SIZE ON CENTER-VIEWING

Introduction

During center-viewing, the information about the targets is only accessible via attentional selection in the periphery. Center-viewing may be used so prevalently because this information is sufficient to maintain representations of their locations. If center-viewing does rely on the ability to access peripheral target information, then limiting the ease of access to this information should decrease the use of the center-viewing strategy. In this experiment the size of the dots in the display were varied so that, in some cases, peripheral vision would not be sufficient to maintain target locations. This created a situation where target fixations and target-to-target saccades should have been used more frequently. The intriguing result from this experiment will be whether or not center-viewing changed when target identities were difficult, if not impossible, to maintain without target-viewing. If center-viewing relies on peripheral resolution to maintain attentional foci on the targets, the strategy should be abandoned when the targets are too small to see in the periphery. If this were the case, gaze would overlap with the targets for the majority of the time and would infrequently overlap with the center. However, if gaze continued to overlap with center even when there was an overall shift to target-viewing, it would support the idea that center-viewing results from grouping the targets into a single virtual object. This is because, according to the object-

based grouping theory, gazing at the center of the object formed by the target helps to reinforce the mental representation of the object and its vertices, the tracking targets.

Methods

The methods for Experiment 2 were the same as in Experiment 1, except for the following alterations.

Participants

Twenty-seven people (5 females; aged 20-33) from Vanderbilt University participated in this experiment following the procedures for the protection of human participants defined in the APA Code of Ethics (2002). Six participants' data were excluded from the final analysis due to a lack of sufficient eye movement data being acquired because of signal loss by the eye tracking equipment (see Results).

Stimuli

To keep the tracking task challenging but not impossible, I chose to use the mid-range speed level of 12°/s from Experiment 1 where tracking accuracy was above chance and below ceiling (~65%). Other important considerations was the relative amounts of center-viewing and target-viewing seen for the different speeds in Experiment 1. At the 12°/s speed the total amount of the center was viewed was roughly equivalent to the sum of the average amount each target was viewed (39% vs. 44%). I chose a speed where the center and the targets accounted for roughly equivalent amounts of time so as to increase the likelihood that they would vary as a function of size. Dot size ranged from a diameter

of 1 to 5 pixels (0.06° to 0.3° degrees). These sizes are roughly 6 times smaller than those used in Experiment 1 and in my previous work. They were chosen based on pilot data with larger sizes (0.15° to 1.9°) that only showed changes in gaze at the very smallest sizes.

Procedure

Participants completed one 60-minute session containing 125 experimental and 5 practice trials. At the beginning of the session and after every block of 25 trials, the eyetracking system was calibrated using a 17-point calibration. There were 5 size conditions tested: 0.06°, 0.15°, 0.18°, 0.24°, 0.3°.

Results

Accuracy was defined as the percentage of trials in which all targets were correctly identified (chance = 0.48%). The average percent correct across all size conditions was 37%, ranging from 0.01-53.9% from the smallest to largest sized dots. An ANOVA on the accuracy data showed a significant main effect of size ($F(4,80)=86.41, p<.01$), indicating that accuracy diminished significantly with the size of the dots. The accuracy was so low at the smallest dot size (0.06°) that only 4 of the subjects managed to successfully track all 4 targets on one trial each, providing an inadequate sample size of correct trials with enough eye data to be analyzed for eye movements. For this reason, I will report the eye movement data of both the correct and incorrect trials to give a more full picture of the eye movement strategy that observers used. Correct trials were again selected for eye movement analysis if less than 10% of

the eye movement data was lost due to errors with the equipment, calibration, or participants' motion (such as blinks or head motion). Data from six participants were removed because their number of excluded trials exceeded 30%. The average number of excluded trials for the rest of the participants was 11.8%.

As in Experiment 1 gaze location was assessed with the location competition analysis as well as the window method where the amount of time that gaze was within a window of each competitor was quantified. However, because dot sizes were much smaller in this experiment, the window used for the analysis was reduced from 5° to 0.6°, twice the size of the largest dot size. The average amount of gaze overlap was analyzed to see if it varied as a function of dot size or dot type (target, distractor, or center). An ANOVA on the correct trials showed that the main effects of dot type ($F(2,36)=79.8$, $p<.01$) and size ($F(3,54)=4.3$, $p<.01$) were significant, as well as their interaction ($F(6,108)=4.6$, $p<.01$). Gaze overlapped with the center (4.0%) much more than the targets (0.9%) or distractors (0.3%). This replicates our previous results; however the percentages of overlap are much lower than previously observed. A look at the simple effects showed that the percentage of overlap with the center lowered from 5.0% to 3.2% as size decreased ($F(3,54)=4.59$, $p<.01$) while the target overlap increased from 0.90% to 1.3% ($F(3,54)=4.35$, $p<.01$). These results from correct trials are plotted in solid lines in Figure 5A.

Data from the location competition analysis revealed a different pattern of results than the window analysis (Figure 5B). This analysis only showed a significant main effect of dot type ($F(2,36)=169.34$, $p<.01$), with the percentage of wins higher for the center (57.4%) than the targets (7.9%) or distractors (1.8%). Because this method of

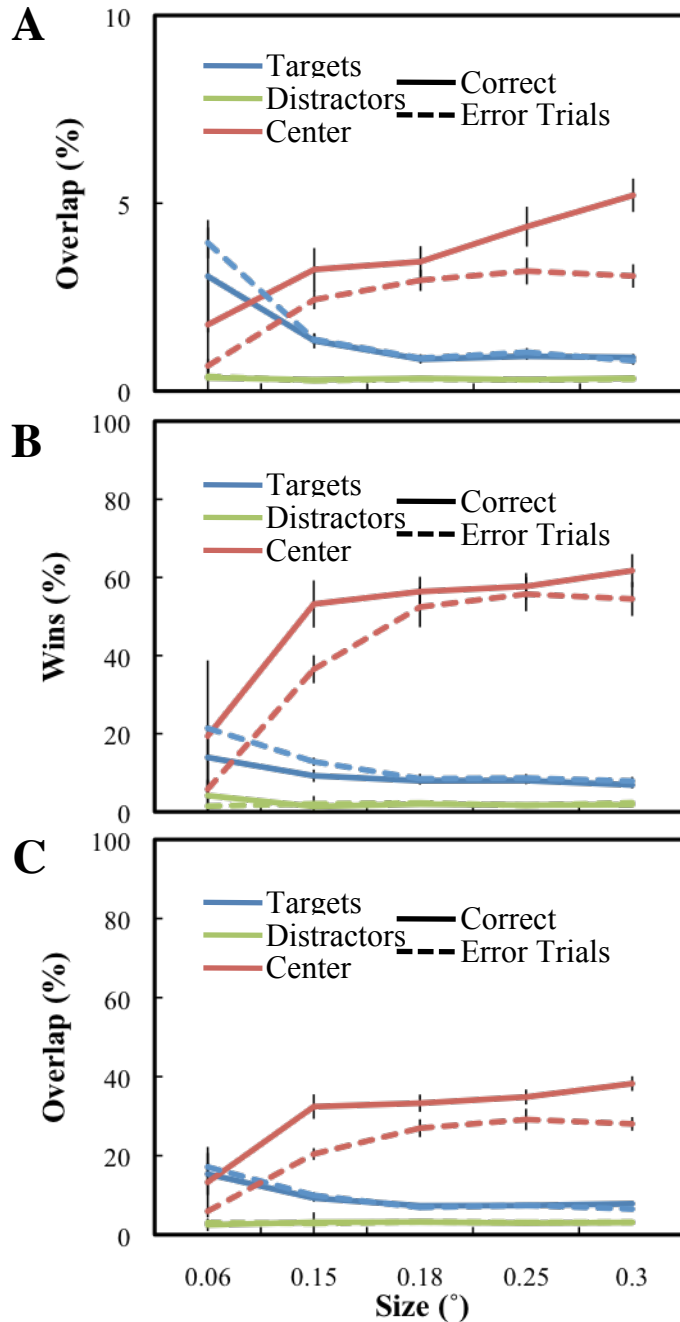


Figure 5: Experiment 2 - Gaze analysis results. (A) Average percentages of the time that any of the targets (blue), distractors (green), or the center (red) overlapped with gaze as calculated by the window analysis. Correct and error trials are shown in solid and dashed lines, respectively. (B) Results of location competition analysis for the correct trials. Colors are the same as in A. (C) Average percentages of gaze overlap in correct trials as calculated by a larger window than in A. Colors same as in A.

analysis is competitive, a winner is assigned on every frame to the closest competitor.

For this reason, the percentages of wins for all the competitors are much higher than the

percentage of gaze overlap found with the window analysis, yet also more susceptible to noise. It may be that effect of size found with the window analysis is washed away with the competitive analysis by an increase in the noise of the added data to each competitor. This idea is strengthened by re-running the window analysis using the window size from Experiment 1 where the dots were roughly 6 times larger. Increasing the window size in this way added more data to each competitor by increasing the chance that gaze would overlap with the larger window. As in the competitive analysis, the enlarged window analysis found only a significant main effect of dot type ($F(2,36)=241.18, p<.01$), with the center overlapping with gaze much more (34.3%) than the targets (7.8%) or distractors (3.1%). These results indicate that the differences between the small window and competitive analysis may be due to an increase in noise. Further, a look at the center data for both analyses (Figure 5B for the competitive and Figure 5C for large window) demonstrates that there is a slight upward trend from dot sizes 0.15° to 0.3° . Overall it seems that as dot size decreased gaze was directed less to the precise location of the center and more to undefined regions near it.

Because participants' error rates were very high, I will briefly discuss the eye movement data from the error trials. Data from the error trials is plotted in the dashed lines in Figure 5A. Overall the amount that gaze overlapped with the center is much lower for the error trials than the correct trials, though this difference is only significant at the largest dot size ($t(21)=3.92, p<.01$). The amount that the targets were viewed rapidly increases for the two smallest size conditions where the accuracy was the lowest, whereas the amount the center was viewed decreases. An ANOVA on this data with dot type and speed as factors indicated a significant main effect of dot type ($F(2,40)=74.91, p<.01$), as

well as a significant Dot Type X Size interaction ($F(8,160)=35.58, p<.01$). A simple effects analysis revealed that the significant interaction was caused by the contrasting increase in the percentage of target overlap from 0.8% to 3.9% ($F(4,80)=75.2, p<.01$) and the decrease in the percentage of center overlap from 3.1% to 0.7% ($F(4,80)=34.2, p<.01$) as dot size decreased. These data indicate that on trials where the observers were unable to keep track of all the targets they spent more of the time looking at targets than at the center of the target array.

Discussion

The purpose of Experiment 2 was to determine if the ease of access to peripheral information is a limiting factor in the choice for observers to engage in center-viewing. Access to peripheral information was limited by decreasing the size of the dots in the display. This manipulation had a strong effect on tracking, as accuracy fell off steeply at the smallest sizes of dots used. The drop in performance at the smallest dot sizes indicates that these stimuli did push observers to their limits of peripheral resolution. The critical finding with these data is that the amount of center-viewing did vary across the levels of dot size that were tested. The center was viewed less when targets were smaller. These results suggest that the ease of accessing peripheral information is a guiding factor in the choice to use a center-viewing strategy of eye movements. The multi-focal theory of tracking relies on location information to update the attentional foci so that they remained centered over each target. In contrast, the object-based grouping theory posits that the positions of the targets are maintained by the mental representation of a virtual object formed by the targets. Whereas an object-based theory predicted that center-

viewing should persist even at the limits of peripheral resolution, these results are consistent with a multi-focal theory of tracking which predicted an abandonment of center-viewing when the targets were difficult to resolve in the periphery. When this location information could not be selected peripherally, it was necessary to move gaze away from the center. These data suggest that keeping gaze rooted at the center of the object formed by the targets is not important for tracking them.

By investigating the error trials I was also able to determine what eye movement patterns participants resorted to when they were unable to resolve all of the targets in their periphery. Similar to the correct trials, the error trials also showed a decrease in the time the center was viewed at the smallest dot sizes with a concurrent increase in the target viewing times. These data suggest that when the perceptual limits of the participants were pushed they may have switched to a target-viewing strategy.

Similar to the results from Experiment 1 where there was a tendency to shift gaze between the center and targets more often when they moved at faster speeds, this experiment showed that targets were viewed more when they were smaller. Together, these data suggest that the more difficult it is to pinpoint a target's location, the more likely people are to make an eye movement to the target to update its location. This method of visual selection seems to supplement the attentional selection of the targets in the periphery when they are highly visible. However, as the targets become more difficult to resolve peripherally, direct visual selection seems to become more critical.

CHAPTER IV

EXPERIMENT 3: CHANGING TASK DEMANDS

Introduction

Experiment 3 explores whether there is a top-down, or goal-directed, contribution to the center-viewing strategy. The goal of this experiment was to determine if center-viewing could be disrupted by altering the goal of the tracking task. The key question in this experiment is whether participants would sway from the center-viewing strategy if one of the targets were more valuable than the others. It is possible that if the incentive to track the targets is not equal among all the targets, participants may try harder to track the more valuable targets while concurrently devoting more attention to them. To see if this was the case, the targets were assigned specific colors that indicated differing points values. If center-viewing is derived from the balancing point between the attentional weights given to each target, the unequal values of the targets may result in a shift of gaze from the center in the direction of the higher valued targets. If, however, center-viewing is a reflection of participants looking at the center of the object formed by the tracking targets, participants will continue to look at the center of that virtual object. The results from this experiment show the extent to which center-viewing is determined by the top-down goals of the observer. Further, they establish the extent to which visual selection during tracking is guided by the distribution of attentional selection.

Methods

The methods for Experiment 3 were the same as in Experiment 1, except for the following alterations.

Participants

Eighteen people (7 females; aged 18-32) from Vanderbilt University participated in this experiment following the procedures for the protection of human participants defined in the APA Code of Ethics (2002). Six participants' data were excluded from the final analysis due to a lack of sufficient eye movement data being acquired because of signal loss by the eye tracking equipment (see Results).

Stimuli

Stimuli were 10 gray dots (1.8°) presented within a white rectangular frame on a black background ($36.8^\circ \times 36.8^\circ$). These dots were slightly smaller dots than those used Experiment 1 (2.1°). All of the dots were gray for the tracking period, but the targets were colored red, blue, or green during the cuing period. During response selection the targets changed back to their original color when they were selected and the distractors mistakenly chosen as targets changed to white. To keep the tracking task challenging but not impossible, I chose to use the mid-range speed level of $12^\circ/\text{s}$ from the Speed Experiment where tracking accuracy was above chance and below ceiling ($\sim 65\%$).

Procedure

Participants completed one 60-minute session containing 108 experimental and 4 practice trials. At the beginning of the session and after every block of 18 trials, the eyetracking system was calibrated using a 17-point calibration. There were always 3 targets designated out of the 10 total dots presented on each trial. The colors of the dots determined the point value that they were worth. Red dots were worth 1 point each, blue dots were 4 points, and green dots were 6 points. The three targets were either all the same color or mixed so that two had the same color (red or blue) and one had a color of higher value (blue or green). There were three types of blocks, each repeated twice in a session, which had same/mixed color pairings that were consistent across a block: (1) with either all red or a 6:1 value ratio with 1 green and 2 red, (2) with either all blue or a 6:4 value ratio with 1 green and 2 blue, or (3) with either all red or a 4:1 value ratio with 1 blue and 2 red. Participants were informed about the point values of each color dot and were told that their goal was to collect as many points as possible by correctly tracking dots. All dots were colored gray during the tracking period. Upon selection by the participant the targets changed back to their original color and distractors turned white. Participants were informed of the total points earned per trial as well as their growing tally at the end of each trial. In addition to the visual feedback, a tone was played upon each selection indicating whether or not the response was correct (high tone for correct and low tone for incorrect responses). The participant was notified of their final point tally at the end of the experiment.

Results

Accuracy was defined as the percentage of trials in which all targets were correctly identified, a result with a chance level of 0.83% (1 correct out of 120 possibilities of choosing 3 out of 10 dots). The average percent correct across all conditions was 79%, ranging from 76-81%. To examine the effect of value on the accuracy the high value targets and the low value targets average percent correct was calculated separately for the different point ratios. An ANOVA with dot value (high or low) and ratio type (6:1, 4:1, or 6:4) as factors revealed a significant main effect for dot value ($F(1,11)=9.99, p<.05$), but not for ratio type ($F(2,22)=1.36, p=.28$). For all three of the ratio conditions, there was higher accuracy for the high value target than for the low value targets (Figure 6). These results suggest that the point value manipulation did

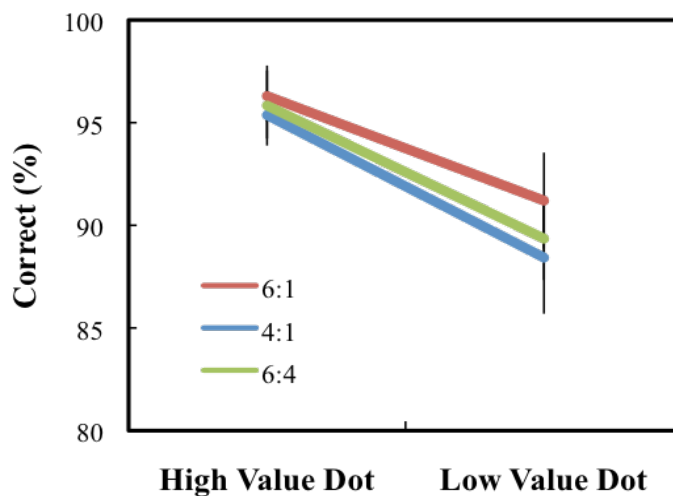


Figure 6: Experiment 3 – Accuracy results. Percentage of correct selections for the high and low value targets in each value ratio combination.

cause subjects to bias their tracking accuracy towards the high value dots. I will now discuss whether this bias was reflected in their eye movements.

Correct trials were analyzed for eye movements if less than 10% of the eye movement data was lost due to errors with the equipment, calibration, or participants' motion (such as blinks or head motion). Data from six participants were removed because their number of excluded trials exceeded 30%. The average number of excluded trials for the rest of the participants was 3.4%. Gaze position was analyzed by calculating the percentage of time during tracking that gaze overlapped with a 5° window around each dot or the center. Average viewing of the center was 42.9%, while the average viewing time for the targets and distractors was 10.9% and 3.7%, respectively. Average percentages of overlap were analyzed to test if they varied as a function of dot type (target, distractor, or center) or trial type (mixed or same). An ANOVA revealed a significant main effect of dot type ($F(2,22)=155.98, p<.01$), but no effect of trial type ($F(1,11)<1$). Thus, though there was a significant difference seen across dot value conditions with regards to accuracy, this was not mirrored by the eye movement data. To determine if there was a bias towards the high value dot when viewing the center, I analyzed only the moments where gaze was classified as at the center by the window analysis and calculated the average angle and distance of the eye from the center with respect to the high value dot. The results of this analysis of gaze deviations towards the high value target did not differ across the Same and Mixed trials. Further, in terms of the time where gaze overlapped with targets, there was a non-significant trend of higher percentages of overlap for the higher valued target than the lower valued targets (12.9% vs 9.7%; $F(1,11)=2.80, p=.12$).

Discussion

This experiment changed the goal of tracking to determine if the center-viewing strategy could be biased by top-down attentional effects. Although higher accuracy was found for the more valuable targets, indicating participants may have attended more to that dot, there was not an associated alteration in the pattern of center-viewing. Though the center was still viewed predominantly, the relative amounts that it, the targets, and distractors were viewed remained consistent across all conditions. There was also no evidence of a tendency for participants to bias their gaze towards the more valued target when viewing the center. This pattern of results suggests that, though the manipulation of value might have shifted more attention to the high value target, the center-viewing strategy does not appear to reflect the balancing point between the attentional weights given to each target. This is not consistent with a multi-focal attention theory of attentional tracking. On the contrary, participants continued to fixate the center of the object formed by the targets, despite their relative values. These results suggest that the center-viewing strategy may be based on grouping the targets into a virtual object and tracking the center of that object. Additionally these findings imply that visual selection does not reflect biases in the distribution of attention.

CHAPTER V

EXPERIMENT 4: MANIPULATING TARGET MOTION REDUNDANCY

Introduction

Experiments 1 and 3 did not find that center-viewing was an attempt to reduce eye movements or a reflection of the balance point of the attentional weighting given to each target. Instead, they each supported the idea that center-viewing may be rooted in tracking the center of the object formed by grouping the targets together. Experiment 4 sought out to directly test this object-based grouping theory by manipulating the ease with which the targets could be grouped together. Participants may view the center more if it is easier to group them into a single object. Redundancy of target motion was varied from completely dependent to completely independent. If center-viewing is related to grouping the targets together, it should vary as a function of target motion redundancy. Alternatively, if center-viewing is not related to the grouping of a virtual object, it may not vary across grouping conditions.

Methods

The methods for Experiment 4 were the same as in Experiment 1, except for the following alterations.

Participants

Thirteen people (7 females; aged 18-33) from Vanderbilt University participated in this experiment following the procedures for the protection of human participants defined in the APA Code of Ethics (2002). One participants' data were excluded from the final analysis due to a lack of sufficient eye movement data being acquired because of signal loss by the eye tracking equipment (see Results).

Stimuli

Stimuli were 6 red dots (1.8°) presented within a white rectangular frame ($36.8^\circ \times 36.8^\circ$) on a black background. Targets were designated by changing their coloration to green during the cue period. Starting positions were randomized, but limited to 9 central positions in order to reduce the amount that the dots bounced off of the walls. When moving independently, each dot moved in a random Brownian-like motion constrained so that each one moves on average a set number of pixels per frame. Three dot speeds were tested, with the dots moving 1 ($\sim 6^\circ/s$), 2 ($\sim 12^\circ/s$), or 3 ($\sim 18^\circ/s$) pixels per frame. The main manipulation in this experiment, however, was the extent of motion redundancy of the targets. When targets moved completely redundantly they were completely yoked. They all moved in the exact same direction, with all the targets changing direction when one of them bounced against the wall. Two levels of partially independent target motion were created by allowing the direction of target motion selected for each frame to vary across targets by either 6° or 12° . In the completely independent motion, the direction of each target was computed separately and allowed the maximum amount of variation across targets (360°).

Procedure

Participants completed one 60-minute session containing 192 experimental and 6 practice trials. At the beginning of the session and after every block of 24 trials, the eyetracking system was calibrated using a 17-point calibration. There were two factors, grouping and speed. Grouping had 4 levels, where the directions of motion varied across the targets by either 0°, 6°, 12°, or 360°. The three speeds were tested were 6°/s, 12°/s, and 18°/s. Each trial began with the 3 targets turning green for 3 s. After a 3 s period of motion participants selected each of the tracking targets with the computer mouse. A high or low tone provided feedback for each correct and incorrect selection, respectively.

Results

Accuracy was defined as the percentage of trials in which all targets were correctly identified, a result with a chance level of 5% (1 correct out of 20 possibilities of choosing 3 out of 6 dots). The average percent correct across all conditions was 95%, indicating that observers were at ceiling performance for this task. Correct trials were analyzed for eye movements if less than 10% of the eye movement data was lost due to errors with the equipment, calibration, or participants' motion (such as blinks or head motion). Data from two participants were removed because their number of excluded trials exceeded 30%. The average number of excluded trials for the rest of the participants was 9.4%.

As in previous experiments, gaze position was determined by calculating the percentage of time during tracking that it overlapped with a 5° window surrounding each

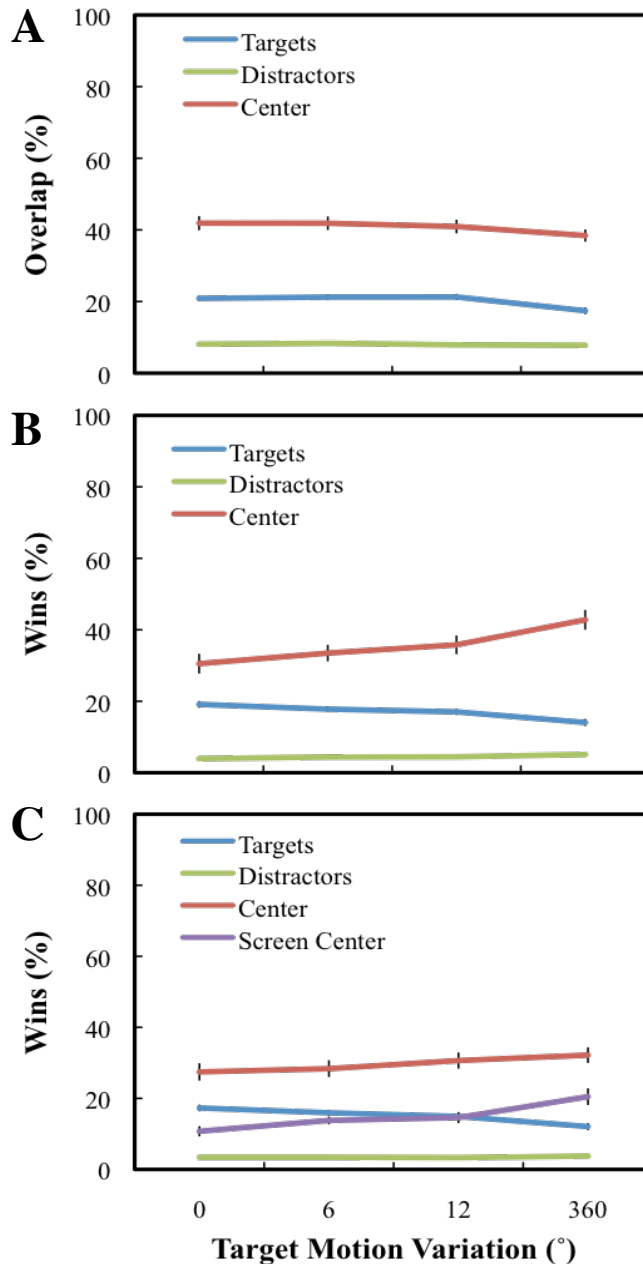


Figure 7: Experiment 4 - Gaze analysis results. (A) Average percentages of time that the targets (blue), distractors (green), or the center (red) overlapped with gaze as calculated by the window analysis. (B) Average percentages of time that the targets, distractors, or center won the location competition analysis. Colors are the same as in A. (C) Results from the location competition analysis with Screen Center (purple) added as a competitor. Colors are the same as in A.

dot or the center in addition to the location competition analysis. Results from the window analysis showed that all three main effects were significant (dot type:

($F(2,20)=106.6$, $p<.01$, speed: $F(2,20)=20.6$, $p<.01$), grouping: $F(3,30)=7.3$, $p<.01$).

None of the interactions of these factors were significant. The significant grouping effect resulted from a trend for targets and the center to be viewed less as grouping decreases (Figure 7A), though this effect was only significant for the targets in simple effects analysis ($F(3,30)=14.6$, $p<.01$). To compare with the results from the window analysis method, an ANOVA was also run on the data from the location competition analysis.

This analysis also found all three main effects to be significant (dot type: $F(2,20)=43.8$, $p<.01$, speed: $F(2,20)=10.5$, $p<.01$, grouping: $F(3,30)=7.5$, $p<.01$). Though these analyses revealed the same main effects, the location competition also found significant interactions (Dot Type X Grouping: $F(6,60)=7.2$, $p<.01$, Dot Type X Speed: $F(4,40)=9.2$, $p<.01$). Simple effects analyses within each dot type revealed that the effect of grouping was significant for both the targets ($F(3,30)=8.8$, $p<.01$) and the center ($F(3,30)=7.2$, $p<.01$). In contrast to the window analysis, however, this effect comes from a trend of viewing the targets less and the center more as the grouping factor increased (Figure 7B).

To try and account for the differences between the window and competition analysis, I ran another location competition analysis with the screen center added as an additional competitor. Because the nature of the location competition analysis is to assign the gaze from every frame to the closest competitor, the competition analysis accounts for more of the viewing time than the window analysis, yet also could be adding noise to the data.

For this reason, we chose to add the screen center as a competitor, as it is likely to account for some of the center data, illuminating the differences in the two analyses. The screen center was thought to account for some of the data attributed to the center because it is often located nearer to the center than any of the dots during tracking. Similar to the

previous competition analysis, all main effects were found to be significant (dot type: $F(3,30)=33.2$, $p<.01$, speed: $F(2,20)=21.0$, $p<.01$, grouping: $F(3,30)=9.7$, $p<.01$). In addition the same interactions were found to be significant (Dot Type X Grouping: $F(9,90)=4.9$, $p<.01$, Dot Type X Speed: $F(6,60)=5.5$, $p<.01$). As the simple effects analysis for each dot type revealed, the center no longer showed a significant effect of grouping ($F(3,30)<2$), though the targets ($F(3,30)=10.7$, $p<.01$) and screen center did ($F(3,30)=14.1$, $p<.10$). As can be seen in Figure 7C, the inclusion of the screen center accounts for most of the increase in percentage of wins at the high levels of target motion variation seen in the data for the center in Figure 7B. In comparison, the percentage of wins for the center in is relatively stable across the different grouping conditions. The percentage of wins for the targets, on the other hand, continues to show a trend of higher target viewing with stronger grouping, while the screen center shows the reverse. Together, these data indicate that the grouping manipulation was most influential on target-viewing, while center-viewing was unaffected.

Discussion

The purpose of Experiment 4 was to determine if the ease with which targets could be grouped together would influence the amount of center-viewing that observers engaged in. The results indicate that the amount of center-viewing was not related to whether the targets were grouped together via common target motion. It was shown, however, that the amount of target-viewing did vary with the grouping manipulation, such that targets were directly viewed more when their motions were linked. It may be that when the motion of the targets is similar or exactly the same, looking at one target is

akin to looking at all of them. By directly looking at one target, the information about its motion is more easily accessed than when it is in the periphery. However, if other targets share the motion properties of the one being foveated, it may be easier to detect them peripherally. Importantly, the independence of the grouping effects for target-viewing and center-viewing indicate that these two eye-movement strategies are not necessarily the converse of each other. In other words, center-viewing is not engaged in as the default alternative to target-viewing. Also notable is that while the center of screen did not account for as much of the viewing time as the center, the amount it was viewed did vary as a function of grouping. Tracking performance was also highly accurate, which may be due to a decrease in the number of distractors from the previous experiments. It is possible that the relative ease of the task might have caused participants to gaze more centrally overall and completely rely on covert attention to track the targets in the periphery. Finally, because these results yielded a null result with respect to center-viewing, they neither support nor refute the theory that center-viewing is tied to a mental representation of the targets forming a single object. It may be that this manipulation of grouping was not strong enough or that tracking was not difficult enough to cause a variation in center-viewing across grouping conditions.

CHAPTER VI

A NEW STRATEGY: CTC-VIEWING

Shifts to targets during center-viewing

The results of the preceding experiments showed that the amount the center was viewed decreased when the targets were difficult to detect peripherally, but was unaltered by changes in speed, value, or motion redundancy of the tracked targets. One common pattern found in all of the experiments, however, was that, though the center was viewed most often, it never accounted for all of the time during tracking. Participants spent a considerable amount of time viewing the targets as well, often switching back and forth between the center and targets. An analysis of these switches revealed a new component of the strategic eye movements used during tracking. In light of these results, I have defined a new strategy of eye movements entitled CTC-viewing (for Center-to-Target-to-Center gaze shifts). Before moving on to Experiment 5, where the efficacy of this strategy was tested, I will describe the analysis of eye movements in which it was revealed.

Streak analysis

In Experiment 1 it was found that the duration of fixations increased as the speeds of dots increased and that switches from one fixation to the next occurred more frequently between the center and targets than between targets. In this analysis, the duration of a fixation referred to the number of consecutive frames a competitor was the

closest to gaze. The frequency of center-to-target switches suggested that there might be an overall pattern of alternating gaze between the center and targets during tracking. To determine if this was the case, I analyzed the eye movement data from Experiments 1-4 for evidence of systematic streaks of alternations between the center and any of the targets. A streak was defined as any repeated alternation between two competitors. For the distractors and targets, it was not necessary to alternate between the same exact dot to be considered a streak. To illustrate this analysis, Figure 8A shows an example of a trial with a total of 15 fixations directed to the center and the various targets. The first 6 fixations would be categorized as a center-to-target streak, as there are three repeated alternations between the center and a target. The next four fixations would be classified as a target-to-center streak. As the only difference between center-to-target and target-to-center streaks was the order of their repeating alternation, their data were combined. And, finally, the following four fixations in the example would be categorized as a target-to-target streak. The fifteenth fixation would not be included in the target-to-target streak as it is not part of an alternation pair. Fixations such as this as well as non-repeating alternation pairs were classified as non-streaks. For each of the streaks, the duration of the streak was calculated by summing the durations of each fixation within the streak. Analysis of the fixation sequences in Experiments 1-4 revealed that the average duration of center-to-target streaks (1.69 s) outweighed the average duration of target-to-target streaks (.31 s). These data are depicted in Figure 8B, with a separate line for each experiment. Note that the trial durations for Experiment 4 were 3 s whereas they were 5 s for Experiments 1-3.

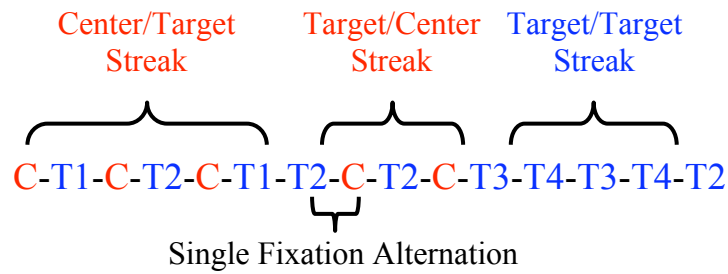
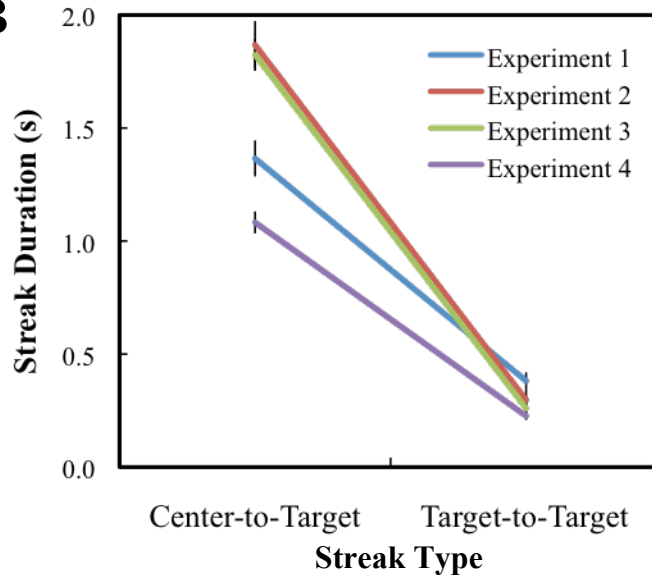
A**B**

Figure 8: CTC-viewing definition and support from streak analysis. (A) Example categorization of 15 fixations of targets (T) and the center (C) into repetitive streaks of center-to-target, target-to-center, and target-to-target alternations. (B) Average durations of center-to-target and target-to-target streaks found across Experiments 1-4.

The CTC-viewing strategy

Given the consistency of the pattern of repeated alternations of gaze between the center and targets, it was clear that the center-viewing strategy, in which people tend to look toward the center, was no longer sufficient to explain the eye movement patterns found during tracking. Instead, the analysis of streaks of fixation alternations indicated

that eye movements during MOT might be better characterized as a goal of keeping gaze at the center with intermittent glances to targets. This new strategy is referred to as CTC-viewing, where “CTC” stands for alternating gaze from the center, to a target, and back to the center. Experiments 1-4 contributed to the discovery of this new eye movement strategy and Experiment 5 will test whether directing gaze in this manner is helpful for keeping track of multiple objects.

CHAPTER VII

EXPERIMENT 5: CTC-VIEWING VERSUS TARGET-VIEWING

Introduction

A central premise in this work is that combining the efforts of attentional and visual selection can help to improve the efficiency with which information can be processed. This is thought to apply to the situation of tracking multiple moving objects because not only are there multiple places to select information from concurrently, but the information must be constantly updated. Of prime importance to this investigation is determining where it is best to direct gaze when attending to multiple targets in order to maximize the selection of information necessary to track them. The previous experiments have all found that a common place to look during tracking is at the center of the target array, with repetitive glances to targets throughout the tracking period. It is not clear, however, if this strategy of eye movements is helpful for maintaining each of the targets. In Experiment 5, I examined whether the CTC-viewing strategy I have found participants to engage in is actually beneficial to tracking performance.

Tracking accuracy was measured when participants followed two different strategies, CTC-viewing and target-viewing. Target-viewing refers to the eye movement strategy of sequentially looking from target to target during tracking. CTC-viewing refers to the eye-movement strategy of keeping gaze rooted at the center of the target array with occasional glances to targets. Each participant alternated use of the two strategies so that their performance between the two conditions could be directly

compared. As a baseline comparison, participants also completed a free-viewing condition where their eye movements were unconstrained. In light of the findings presented in Chapter VI, participants were given information on how to engage in each strategy that included details about shifts of gaze (see *Procedure*). The results of this experiment determine the differential impacts that the CTC-viewing and target-viewing strategies have on successful tracking.

Methods

The methods for Experiment 5 were the same as in Experiment 1, except for the following alterations.

Participants

Twenty-five people (13 females; aged 18-25) from Vanderbilt University participated in this experiment following the procedures for the protection of human participants defined in the APA Code of Ethics (2002).

Stimuli

Stimuli were 12 red dots (1.8°) presented within a white rectangular frame ($36.8^\circ \times 36.8^\circ$) on a black background. Targets were designated by changing their coloration to green during the cue period. Each dot moved in a random Brownian-like motion constrained so that each one moves on average 2 pixels per frame ($\sim 12^\circ/s$).

Procedure

Participants completed two 60-minute sessions containing a total of 240 experimental and 11 practice trials. At the beginning of each block of 20 trials, the eyetracking system was calibrated using a 17-point calibration. All dots moved at a speed of roughly 12°/s. Each trial began with the 3 targets turning green for 3 s. After a 3 s period of motion participants selected each of the tracking targets with the computer mouse. A high or low tone provided feedback for each correct and incorrect selection, respectively.

In the first session, participants were not informed of either strategy and were allowed to freely view during tracking. They were also asked to try and indicate their tracking errors by pressing the space bar when they thought they might have lost a target. These instructions were explained in a written sheet as follows:

In this experiment you will have to keep track of a few target dots that will be moving around the display amidst distractors. Your goal is to keep track of all the targets to be able to select them at the end of each trial. If you lose a target, please press the spacebar as soon as you notice that you have lost it. If you lose multiple targets during a trial, you should press the spacebar for each one. Nothing will happen when you press the spacebar, but we will record your responses to determine how well you know when you have lost a target. Your eye movements will be tracked during this experiment, but you are free to look wherever you like while you are tracking the target dots. Here are some practice trials so that you can familiarize yourself with the task.

Any questions the participants had were answered at this point and they were then given 3 practice trials. The first session consisted of 6 blocks of 20 trials each, a total of 120 trials. Participants returned the following day to complete the second session.

In the second session each participant completed another 6 blocks of 20 trials each, making a total of 120 trials. There were two blocks (40 trials) for each strategy,

CTC-viewing and target-viewing, as well as two blocks of free-viewing. To emphasize the importance of looking at the center, the CTC-viewing strategy was referred to as center-viewing in all the materials the participants saw. The first block for every participant was a free-viewing block. The order of the following blocks was counterbalanced by assigning each subject to one of five independent orderings created using a reduced Latin square. There were five subjects in each possible block ordering. The same 120 trials were used throughout the experiment and each participant was meant to see each one twice overall (once each session). However, due to a programming error, not all participants saw each trial and many trials were repeated within a session. The order of trials, as well as which trials were seen, was randomized for each participant so that they saw each trial between 0 and 4 times throughout the course of the experiment. Within each session, 50 of the trials were shown twice and 20 were shown only once. In the second session, 10 of the repeats were free-viewing, 20 were target-viewing, and 20 were CTC-viewing. Within a session repetitions always occurred in the following block, such that they were shown 10 trials after the first instance and the first and last 10 trials were never repeated in the same session. Due to trial order randomization, the number of trials repeated across sessions varied for each subject from 37 to 45, with an average of 7.9 free-viewing, 16.1 target-viewing, and 16.2 CTC-viewing repetitions. Upon arriving for the second session, participants were given written instructions explaining the task for their first block of free-viewing as follows:

Today you will be doing the same tracking task as you did in your last session, however you will not have to indicate when you lose track of targets. Your eye movements will also be tracked during this experiment. Look wherever you like while you are tracking the target dots. You'll now do some practice trials so that you can re-familiarize yourself with the task.

They were then given 2 practice trials to remind them of the task. Before the first target-viewing block, participants were given a written explanation of the strategy:

During the next block you will be tracking moving dots again but you are meant to use a particular eye movement strategy called **Target-viewing** while you keep track of the target dots. Instead of looking wherever you want, I want you to keep your gaze near a target. **When you look away from one target, be sure to look at another target.** You are not required to view targets in a certain sequence. You'll now do some practice trials so that you can familiarize yourself with the strategy.

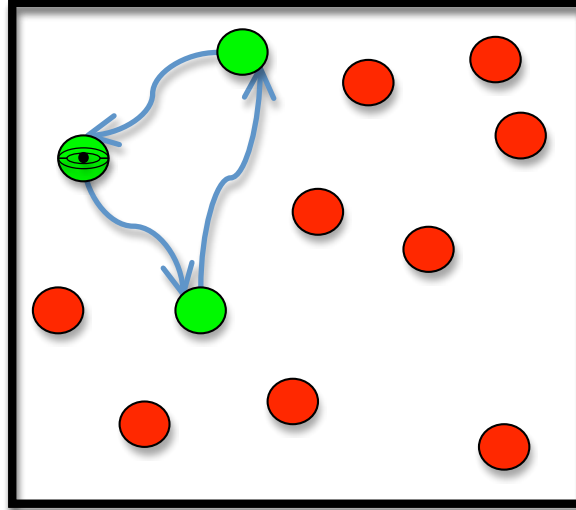
They were then asked if they had any questions about the strategy and were shown a visual aid (Figure 9A) to clarify their interpretation of the instructions. Participants often asked how many targets they needed to look at. I clarified that they did not need to look at any particular number of targets, but that they needed to always be looking at one of them. After their questions were answered, they were given 3 practice trials to try using the target-viewing strategy. During practice eye movement patterns were visually inspected by the experimenter by watching the monitor with eye position overlaid on a depiction of the display screen. If their eye movements did not seem to reflect the strategy that was instructed, the experimenter would further clarify the instructions.

Before the first CTC-viewing block, participants were given a written explanation of this strategy:

During the next block you will be tracking moving dots again but you are meant to use a particular eye movement strategy called **Center-viewing** while you keep track of the target dots. Instead of looking wherever you want, I want you to keep your gaze **near the center point of the targets or** near a target. **When you look away from the center to look at one target, be sure to look back at the center before looking at any other target.** You are not required to view targets in a certain sequence. You'll now do some practice trials so that you can familiarize yourself with the strategy.

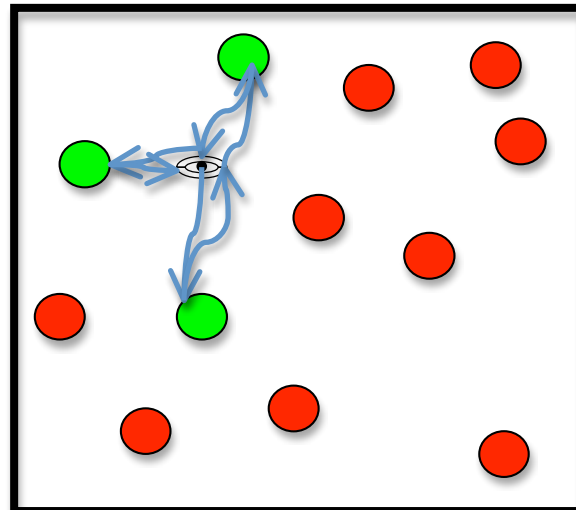
Participants were again shown a visual aid (Figure 9B) to clarify their interpretation of the instructions and asked if they had any questions about the strategy. Some participants asked if the center referred to the center of the display screen. I clarified that they were

A Target-viewing Strategy



Always look at one of the targets and do not look at the center of the targets.

B Center-viewing Strategy



Always look at the center of the targets or at one of the targets.

Figure 9: Experiment 5 - Visual aids for strategies. (A) In the target-viewing condition, participants were told to always look at one of the targets, but not at the center. (B) In CTC-viewing condition, participants were told to look at the center or at one of the targets.

to view the center of the group of targets, not the center of the screen, and that this center point would thus be moving as the targets moved. After their questions were answered,

they were given 3 more practice trials to try using the CTC-viewing strategy. During the practices, subjects were again given feedback about their eye movements if they did not seem to follow the instructions given to them. As a reminder, a shortened version of the written instructions for each strategy was shown at the beginning of each block, as follows:

Free-viewing Instructions

During this block you should try to track all of the designated targets as they move around. While you are tracking the dots you should look **WHEREVER you want**.

Target-viewing Strategy Instructions

During this block you should try to track all of the designated targets as they move around. While you are tracking the dots, you should always look at one of the targets. **Do not look at the center of the targets.**

CTC-viewing Strategy Instructions

During this block you should try to track all of the designated targets as they move around. While you are tracking the dots, you should always look **at the CENTER of the targets or** at one of the targets.

At the end of the second session, participants were asked which of the two strategies they preferred and why they preferred it.

Results

Tracking accuracy

The focus of this experiment was the effect of the eye-movement strategy manipulation on tracking accuracy. Accuracy was measured as the percentage of trials in which all the targets were correctly selected at the end of the trial, a result with a chance level of 0.45% (1 correct out of 220 possibilities of choosing 3 of 12 dots). Average performance for the first session, in which all trials were Free-viewing, was 80.4%. The

accuracy of Free-viewing trials in the second session was 82.5%, which did not differ significantly from the first session data ($F(1,24)=2.02, p=.17$). Changes from the first session were seen in both strategy conditions, however, as performance lowered to 57.0% during target-viewing and 76.7% during CTC-viewing (Figure 10). An ANOVA on the

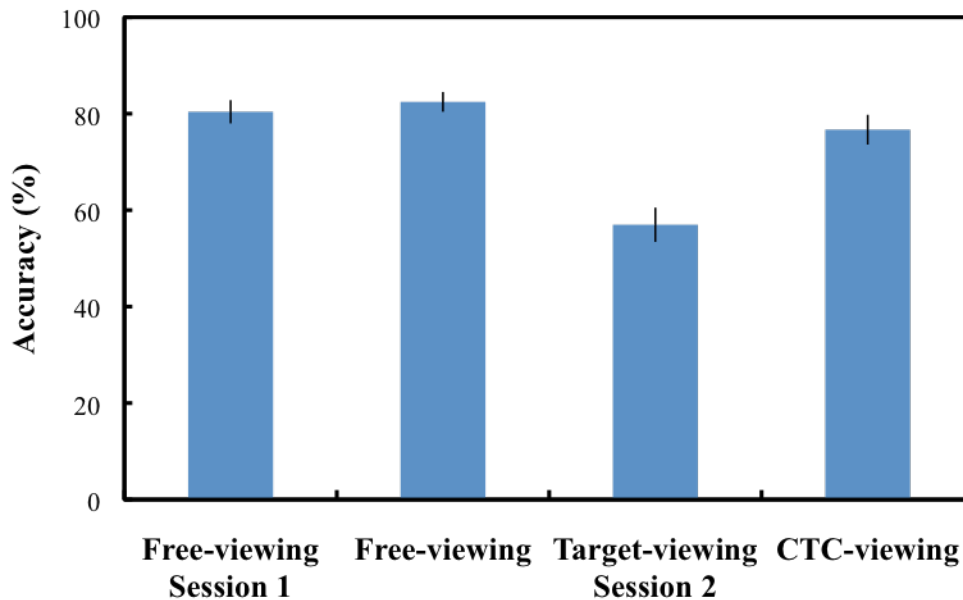


Figure 10: Experiment 5 - Tracking accuracy. The percentage of trials where all targets were correctly selected is shown for each condition (free-viewing, target-viewing, and CTC-viewing) for each session (only Free-viewing trials were shown in session one).

second session accuracy data confirmed that there was a significant main effect of instructions ($F(2,48)=52.6, p<.01$). These data indicate that adding the constraint of a specific eye-movement strategy did reduce accuracy for both CTC-viewing ($t(25)=2.15, p<.05$) and target-viewing ($t(25)=10.02, p<.01$), though there seemed to be a benefit from engaging in the CTC-viewing strategy rather than the target-viewing strategy ($t(25)=7.62, p<.01$).

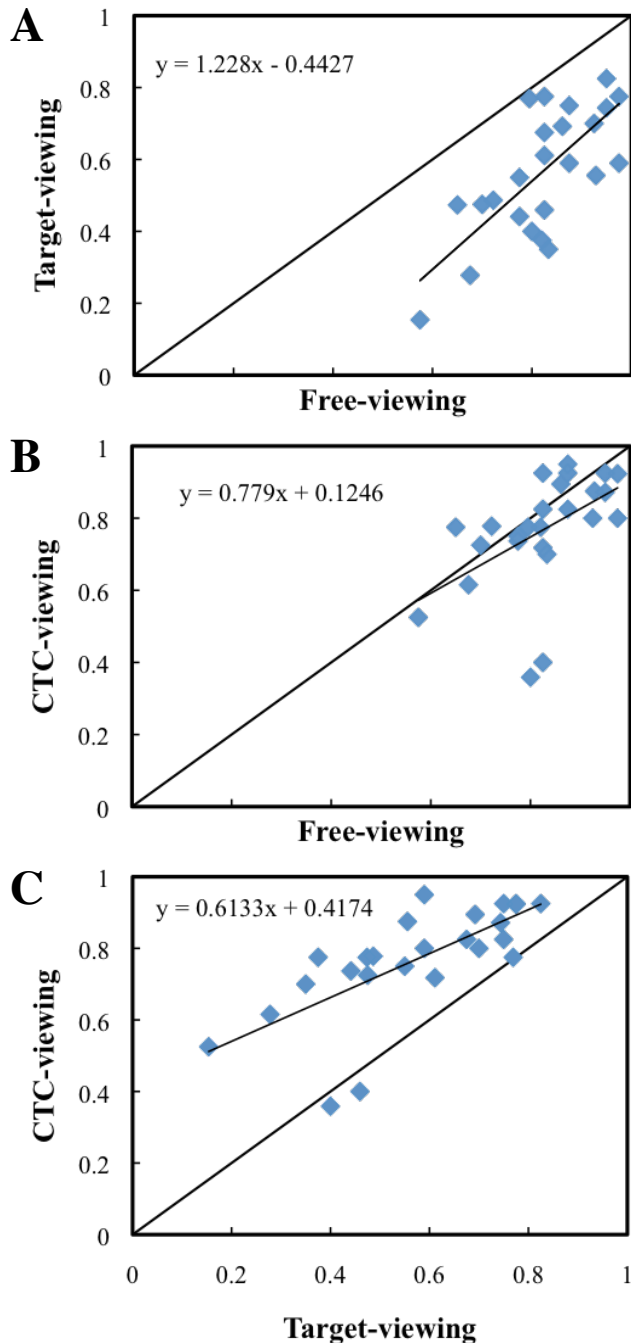


Figure 11: Experiment 5 - Individual differences in tracking accuracy. (A) Percentage correct across free-viewing trials is plotted against target-viewing performance. (B) Free-viewing performance is plotted against CTC-viewing accuracy. (C) Target-viewing performance versus CTC-viewing performance.

A look at the individual variations across strategies shows that this was not the case for every single subject. There are two participants who do not appear to receive a

benefit from engaging in CTC-viewing as compared to target-viewing, however, as can be seen in Figure 11C. These participants performed relatively equivalent with each of the strategies, while most of the other participants show higher performance with CTC-viewing. This difference does not seem to stem from a target-viewing advantage, however, as, similar to the rest of the participants, their target-viewing performance is impaired relative to free-viewing (Figure 11A). Thus, while the majority of subjects show similar performance for CTC-viewing and free-viewing, some variations from this pattern do exist. One cannot infer too much from these variations, however, as a much larger sample of participants would be needed to fully examine the effects of individual differences.

Because all participants were shown anywhere from 0-4 repetitions of each of the 120 trials, it is possible that the accuracy differences across conditions may be confounded with the number of times a trial was seen within a condition. To determine if this was the case, I examined the data for an effect of trial repetition, which has been shown to improve accuracy over time by other researchers (Makovski et al., 2008). To do this, the accuracy for each trial repetition was averaged for only the free-viewing trials from both sessions (Figure 12A). No effect of trial repetition was found ($F(3,72) < 1$). This null effect does not replicate the effect of trial repetitions found by Makovski and colleagues (2008). This difference may be due to the relatively few number of repetitions, however, as their design incorporated 15-20 repetitions of the same 8 trials. To rule out the possibility that the unequal numbers of trial repetitions across conditions may have confounded the significant main effect of instructions reported above, I re-examined the accuracy using only the data from trials that were seen for the first time in the second

session. This reduced the data from 40 trials for each condition per subject to an average of 12.5, 8.6, and 8.4 trials per subject for free-viewing, target-viewing, and CTC-viewing, respectively. Results can be seen in Figure 12B. Despite the reduction in data, the effect of instructions remained significant ($F(2,48)=25.4, p<.01$). The consistency of this pattern of accuracy across strategies suggests that these results were not spurious and did not suffer from an influence of trial repetition.

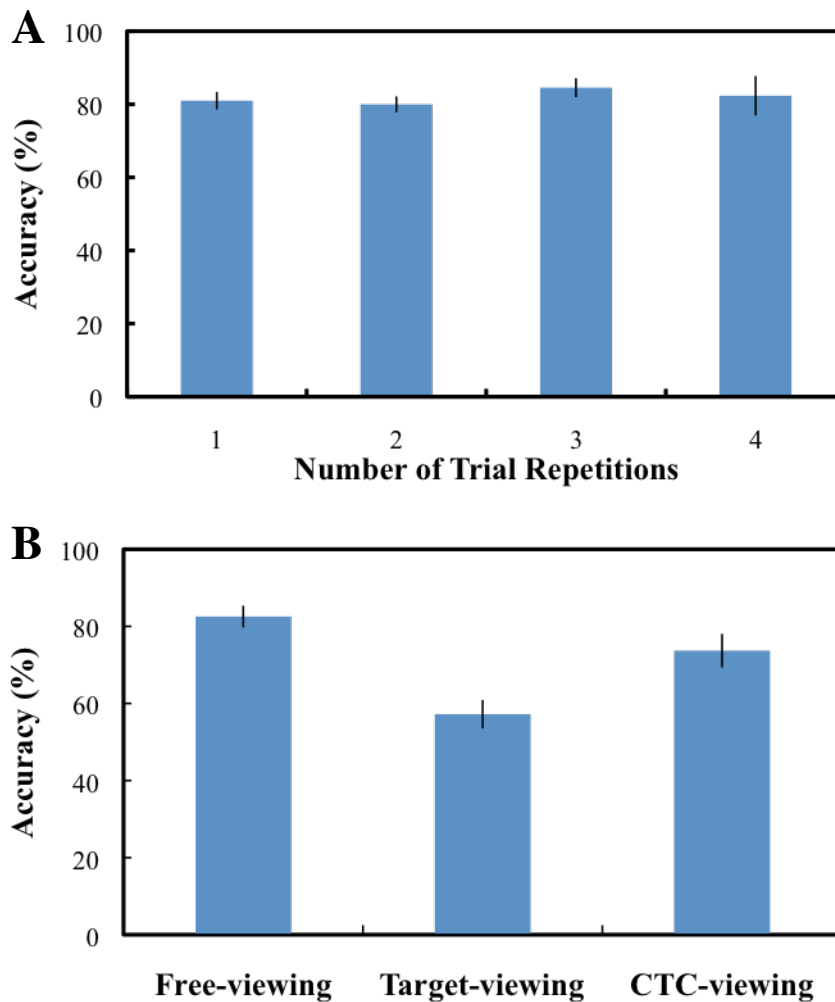


Figure 12: Experiment 5 - Trial Repetition Analysis Results. (A) Accuracy of free-viewing trials across number of repetitions shown. (B) Tracking accuracy using only the first repetition of trials seen for the first time in the second session.

Eye movement analysis

As in previous experiments, correct trials were analyzed for eye movements if less than 10% of the eye movement data was lost due to errors with the equipment, calibration, or participants' motion (such as blinks or head motion). The average number of excluded trials across participants was 5.6%.

Gaze position was again determined by both the window and location competition analysis methods. As there were no differences between the two, only results from the window analysis will be discussed. Similar to results of previous experiments, the data from session one (Figure 13A) showed a significant effect of dot type ($F(3,72)=153.4$, $p<.01$), with a higher percentage of overlap for the center (40.2%) than for the targets (12.7%), distractors (3.8%), and the screen center (17.4%). Data from the second session were analyzed with respect to the effect of dot type as well as the instructions given to participants. This analysis revealed that there was a significant effect of dot type ($F(3,72)=306.7$, $p<.01$) and instructions ($F(2,48)=58.4$, $p<.01$), as well as a significant interaction between the two ($F(6,144)=72.8$, $p<.01$). A look at the simple effects for each dot type shows a significant effect of instructions for each one (Center: $F(2,48)=74.1$, $p<.01$; Targets: $F(2,48)=108.5$, $p<.01$; Distractors: $F(2,48)=12.3$, $p<.01$; Screen Center $F(2,48)=46.6$, $p<.01$). These differences across instructions can be seen in Figure 13B.

To supplement these eye movement analyses, the streaks of fixation alternations were also examined. As was found in Experiments 1-4, the durations of center-to-target streaks was significantly greater than the target-to-target streaks for both session one ($F(1,24)=219.7$, $p<.01$) and session two ($F(1,24)=328.2$, $p<.01$). Additionally, there was

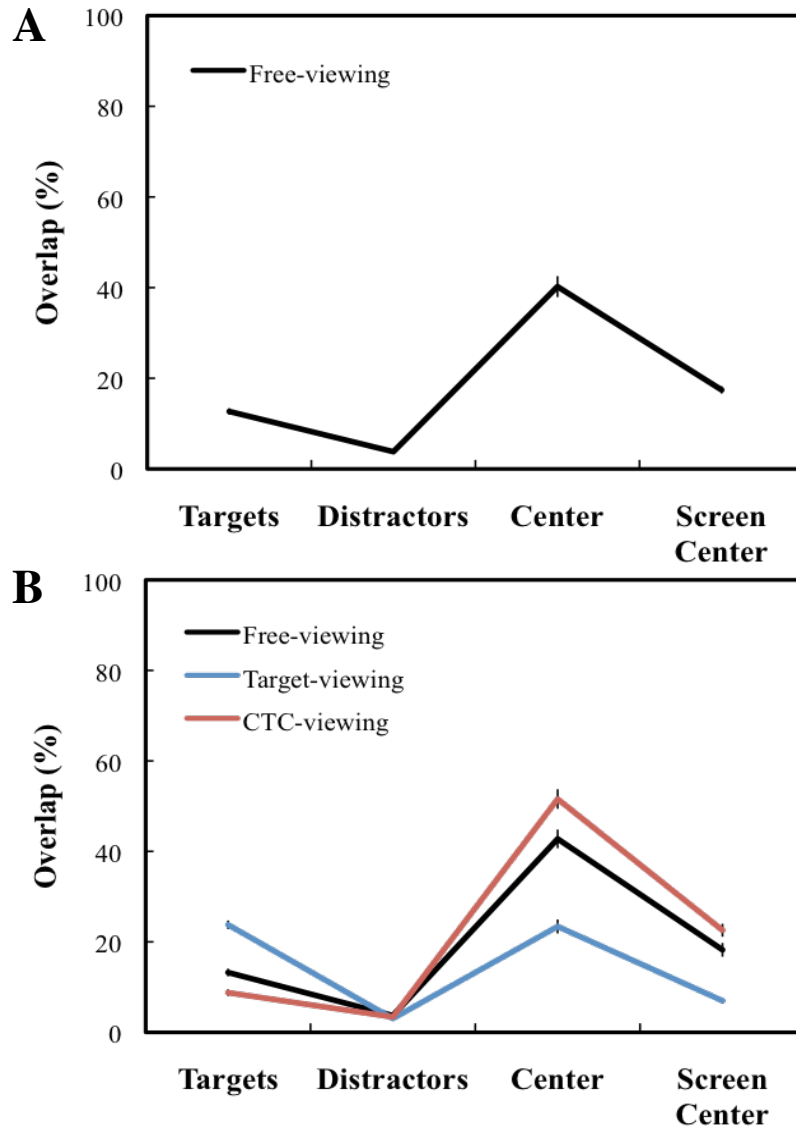


Figure 13: Experiment 5 - Gaze analysis results. (A) Average time in Free-viewing trials in session one that the targets, distractors, center, or screen center overlapped with gaze as calculated by the window analysis. (B) Viewing times as in A for the second session, where instructions varied between free-viewing (black), target-viewing (blue), and CTC-viewing (red).

a significant main effect of instructions in session two ($F(2,48)=3.2, p<.05$), as well as a significant Streak Type X Instructions interaction ($F(2,48)=7.7, p<.01$). As shown in Figure 14B, all instruction conditions show a substantial decrease in the amount of target-

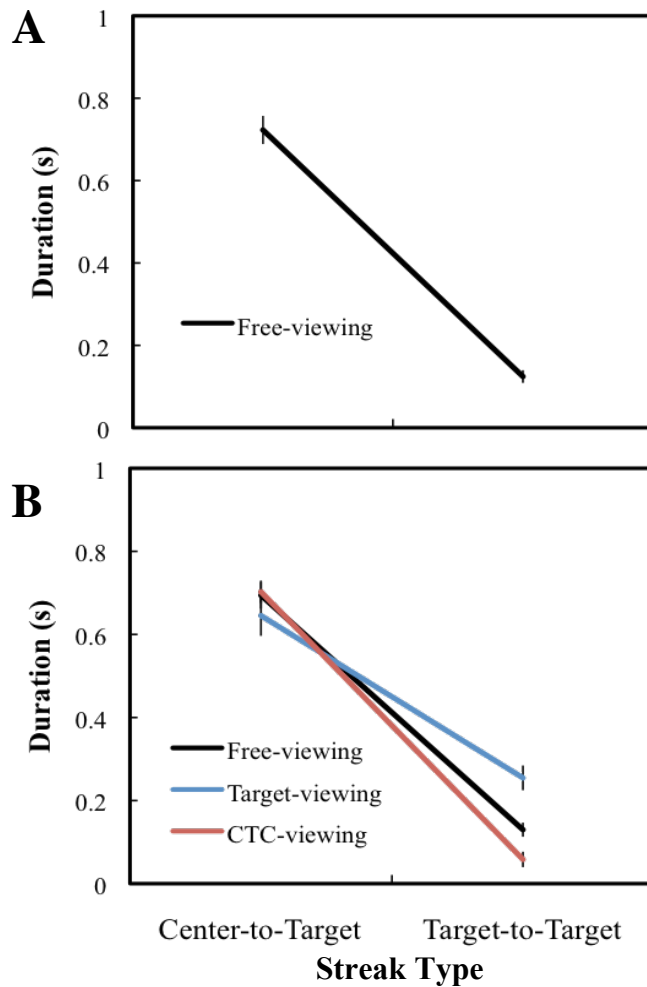


Figure 14: Experiment 5 - Streak analysis results. (A) Average durations of streaks of center-to-target and target-to-target streaks from session one. (B) Same as in A for second session where instructions were to engage in free-viewing (black), target-viewing (blue), or CTC-viewing (red).

to-target relative to center-to-target streaks. While the duration of target-to-target streaks varies as expected across the instructions, the centroid-to-target streak durations do not differ greatly. Taken together, these eye movement analyses do indicate that, on average,

participants changed their eye movement behavior to look more at the targets and less at the center during target-viewing, as well as the converse during CTC-viewing.

It is possible that participant's compliance with the instructed strategies varied across trials or that some trials proved more difficult for one strategy or another. I examined the data from each trial to determine if participants followed the appropriate eye movement strategy. Using a strict criterion of zero center-to-target streaks on target-viewing trials and zero target-to-target streaks on CTC-viewing, I found that 41% of target-viewing and 92% of CTC-viewing trials with fixation alternations passed. These data only reflect trials fixation alternations, which is roughly 21% of the target-viewing trials 60% of the CTC-viewing trials. Because of the limited number of trials with streaks, I relied on the data from the window analysis to assess the strategy compliance of each trial. I used a criterion that was based on the average viewing times for targets and the center across the trials from the first session. To qualify as a successful target-viewing trial, subjects had to have viewed the targets more than they did on average in session one and viewed the center less than in session one. For a trial to be considered a successful CTC-viewing trial, the time the center was viewed had to have increased from the session one average and the time that the targets were viewed had to have decreased. Using these criteria, each trial was classified as a success or a failure to comply with the strategy instructions. Target-viewing was found to have significantly more successful trials (71.6%) than CTC-viewing (36.8%) did ($F(1,24)=45.7, p<.01$). However, as can be seen in Figure 15, both successful and failure trials show improved accuracy for CTC-viewing relative to target-viewing trials (76.0% vs. 53.3% for Success and 80.3% vs. 61.0% for failure). An ANOVA of these data show the main effect of instructions is

significant ($F(1,24)=34.7, p<.01$), but the effect of success was not ($F(1,24)=3.1, p=.09$). These data show that even when the data is reduced to looking at only those that exhibit signs of following the strategy indicated, there is still a clear benefit seen in tracking performance during CTC-viewing trials relative to target-viewing trials.

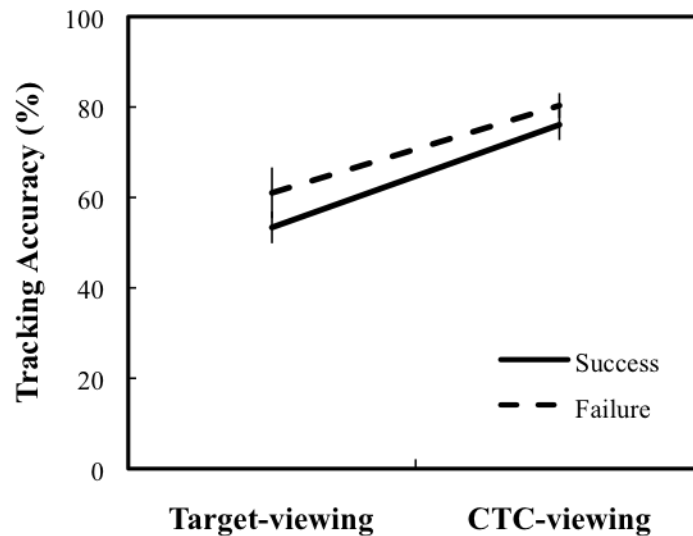


Figure 15: Experiment 5 - Tracking accuracy as defined by strategy success. Accuracy for target-viewing and CTC-viewing trials for trials which did (success, solid line), or did not (failure, dotted line) meet the criterion for adhering to the instructed eye movement strategy.

Discussion

The goal of Experiment 5 was to determine if engaging in CTC-viewing would improve tracking performance relative to an alternative eye movement strategy, target-viewing. To examine this in relation to participants' natural tendencies, each participant performed a full session of tracking where eye movements were not constrained. Then, they returned the following day for a second session in which they were instructed to

engage in either a CTC-viewing or target-viewing eye movement strategy or were allowed to continue free-viewing during tracking. Results indicated that performance was higher when participants engaged in CTC-viewing than when target-viewing. Importantly, this difference remained even when only trials that passed a criterion for strategy adherence were included. These results indicate that CTC-viewing is more beneficial to tracking performance than target-viewing. It is essential to note, however, that performance in both strategy conditions was impaired relative to the free-viewing condition where participants' eye movements were unconstrained. Further, trials that did not pass the criteria for adherence to the instructed strategy actually showed higher accuracy for both conditions than those that did qualify. It appears that while CTC-viewing did result in better performance than the target-viewing, it is not an accurate description of participant's natural behavior during tracking. Both the viewing time and the streak data show that the free-viewing pattern of results was more similar to the CTC-viewing than to the target-viewing pattern. However, neither strategy perfectly replicated the free-viewing pattern. The development of the CTC-viewing strategy is a start, but much more specification is needed to account for all of the eye movements made during tracking. In sum, CTC-viewing as it is defined in the present study is beneficial to tracking, but not as helpful as allowing participants to perform as they would naturally, a strategy that the working definition of CTC-viewing only approximates.

CHAPTER VIII

GENERAL DISCUSSION

Summary of Results

Eye movements can be used strategically to aid attentional selection when attention is required in more than one location. The goal of this study was to investigate a specific eye movement strategy, center-viewing, that I have found participants to engage in when simultaneously attending to multiple objects. I have tested two potential theoretical explanations of center-viewing by determining if certain components are involved in the choice to use it. First of all, center-viewing does not seem to be a compromise made because people are attempting to avoid making costly eye movements. Participants continued to gaze at the center even when the targets moved slowly enough to lower the risk of losing one due to a saccade. Thus, targets were looked at freely if there was time, but the center was never completely abandoned. Second, it was found that the ease of accessing peripheral information is a guiding factor in the choice to use center-viewing. Participants viewed the center less when the targets pushed their limits of peripheral detection. Third, the tendency to view the center does not seem to result from the top-down attentional weighting given to each target. When tracking accuracy demonstrated a bias for participants' to focus more on a higher valued target, this bias was only reflected in the amount the targets were viewed. There was a slight tendency to look more at the higher valued target, but there was no evidence that participants viewed a center point that was shifted towards this target. Fourth, center-viewing does not seem

to rely on the ease with which the targets can be grouped together. Participants viewed the center just as much when the targets' motions were completely yoked as they did when they were totally random. The redundancy of target motion did influence the extent the targets were viewed, however, suggesting that looking at targets may be more beneficial if they contain information about the trajectory of the other targets. Finally, center-viewing was found to be an insufficient description of the eye movements made during tracking. Analysis of the patterns of fixation sequences found that views of the center frequently alternated between the center and one of the targets. Upon discovery of this tendency of alternations, I formulated a new eye movement strategy, CTC-viewing. In this strategy, gaze is rooted at the center, but often shifts back and forth between it and targets. CTC-viewing does appear to be an effective eye movement strategy for keeping track of multiple objects. When compared to target-viewing, most all participants benefited from utilizing CTC-viewing. As it is currently defined, however, CTC-viewing seems to only be an approximation of how people naturally move their eyes when attending to multiple places. Participants showed improved performance when they were allowed to freely move their eyes during tracking as compared to when they were moving their eyes according to the CTC-viewing instructions. The search for all the elements that are factors in choosing where to look when attention to multiple items is required must still continue, though looking towards the center of them is an important one.

Theoretical Implications

An additional aim of this study was to attempt to discover more about the cognitive mechanisms involved in tracking by testing components of center-viewing. The implications for the theoretical explanations behind center-viewing are discussed in light of the present results. Two potential theories of center-viewing were considered, an object-based grouping account and a space-based multi-focal account. Both of these theoretical accounts of center-viewing were supported by different results.

According to the space-based multi-focal account, each object is tracked by directing attentional foci to the location it occupies and updating its representation over time. Gaze then floats to the balance point between these attentional foci. In this framework it is critical that each target can be discerned peripherally and refraining from making extraneous eye movements is a way to avoid losing targets during saccades. I did not find, however, that center-viewing decreased when dot motion was slowed to make saccades less costly. In fact, even more saccades were made at faster speeds as the targets were briefly viewed between fixations of the center. However, center-viewing did decrease when dot size was lowered such that targets were at the limits of peripheral detection. The combination of these results suggests that the ease of access to targets is a guiding factor behind the strategy, but that eye movements during tracking may not substantially limit access to targets. This evidence suggests that the attentional foci directed to each target must be quite robust in order to sustain the disruption of motion continuity caused by saccades away from a target, as well as be able to select the locations of targets that are barely detectable. A better test of this theory that would tax attentional demand at each of the target's location may be to manipulate the spacing of

the dots, as crowding is known to be an important factor for tracking and could cause competitive interactions between foci surrounding nearby targets (Shim et al., 2008). A more direct test of the theory that center-viewing stems from the balance point of multi-focal attention was conducted in Experiment 3. Participants preferentially tracked the higher valued targets and it is assumed that this reflected an attentional bias towards that target. This bias was not reflected in their eye movements, however, as center-viewing was equally used when the targets were of equal value as when they were mixed. This result suggests that center-viewing does not reflect the top-down attentional weighting given to each target.

The alternative theory of center-viewing I have considered is that the targets are grouped into a single object and gaze is rooted to the center of that object. In this object-based framework the representations of the targets are reinforced by the mental conception that they are the vertices of a virtual object. The data from Experiment 1 were consistent with the object-based theory, as it was found that the center of the object was viewed regardless of the speed with which its vertices moved. In contrast, Experiment 2 found that the center of the virtual object was viewed less the more difficult it was to detect the peripheral targets. Given these results, the object-based theory can only account for center-viewing if the grouping process that forms the object representation is assumed to break down when targets are difficult to detect. When the contribution of grouping strength was directly tested, however, this object-based theory was not well supported. Experiment 4 manipulated the strength with which the targets' motion was yoked, making it easier to group them together into a virtual object. If viewing the center of the targets were related to perceiving them as an object, center-

viewing would have varied as the ease of grouping them was altered. It seems that the tendency to center-view may not be well explained by an underlying grouping process that reinforces the mental representation of the targets by grouping them together.

Ultimately, the results of these experiments suggest that neither the balance point of multi-focal attention nor the object-based grouping theories are sufficient explanations for why people tend to look at the center of the objects they are tracking. In order further investigate the nature of center-viewing, it will be necessary to clarify the role that targets play in the strategy. All of the present experiments found that recurring shifts between the center and targets were prevalent. Indeed, the center-viewing strategy was laid to rest in favor of the CTC-viewing strategy, whose definition incorporates these frequent center-to-target alternations of gaze. The key to determining when it is important to look at the center will be to discern when directly looking at the targets is critical.

Defining CTC-viewing

My initial exploration of eye movements during tracking found that participants spent more time looking at the center of the target array than at any other point in the display, including the targets. I originally labeled this tendency center-viewing and contrasted it with target-viewing, a pattern of eye movements where the targets are mainly viewed during tracking. However, in consideration of the present work, the center-viewing strategy was abandoned. A common pattern that emerged in these results is that participants frequently alternated between looking at the center and looking at targets. This finding provided the framework for a more dynamic strategy, CTC-viewing, which stands for center-to-target-to-center alternations. In this strategy, gaze is

anchored at the center, but glances to targets are performed as necessary. In contrast, target-viewing consists of directing gaze to one target at a time and switching between them when necessary. These strategy definitions were the basis for the instructions participants received in the final experiment.

As seen in Experiment 5, tracking performance benefited from using the CTC-viewing strategy relative to the target-viewing strategy. However, it is interesting to note that the success and failure rates of these strategies on individual trials were quite different. Participants were much better at complying with the target-viewing instructions than with the CTC-viewing instructions. The success rate was based on the change from the average times that the center and targets were viewed in the first session when free-viewing was allowed. Because the target and center averages in the free-viewing condition were more similar to those during the CTC-viewing instructions than the target-viewing, it was more difficult for trials to pass the success criteria for CTC-viewing than target-viewing. Thus, it is possible that the success rate for CTC-viewing was lower because the free-viewing strategy participants closely resembled CTC-viewing. An additional factor that may have influenced the success rate is that the CTC-viewing instructions may be inherently more difficult to follow because it requires the online computation of the center of mass of the targets. Perceptual estimations of the center of stationary dots have been shown to be influenced by symmetry and elongation (Friedenberg & Liby, 2008), thus it stands to reason that some configurations the targets form as they move might produce more errors in determining the center. It may be that the differences between the free-viewing and CTC-viewing conditions come from participants performing more taxing mental computations to fixate the actual center of the

targets, while their natural tendency could be to stray from the center under certain circumstances. The nature of these circumstances and the point to which gaze veers is yet to be determined. The obvious starting point for further investigations is the relationship between gaze and the targets.

The difficulty with tracking that results from looking at targets is not straightforward. The targets are clearly important to gaze placement during tracking, as they are what is being attended. Yet requiring observers to always look at them made it harder to keep track of them. All but three of the twenty-five participants in Experiment 5 reported verbally after the experiment that they preferred the CTC-viewing strategy because it was too easy to lose track of targets while they were target-viewing. It may be that shifting gaze to the targets is helpful to tracking only if the timing of gaze shift is appropriate. Determining when the best moment is to look at targets might be a crucial part of CTC-viewing. It is possible that participants focused on the center to determine when they should shift gaze to targets.

The primary question remaining, then, is where the need to look at targets comes from. The current work suggests that targets are viewed much more when they are too small to see peripherally, moving very slowly, or moving in the same way as their partners. These are based on overall averages, however, which blur the particular temporal patterns of when shifts are made in relation to certain parameters. For instance, gaze may be shifted from the center to a target if that target is crowded by distractors. Similarly, gaze may be shifted away from a target and back to the center when the target ceases to be crowded by the distractors. As crowding has been shown to be a strong limiting factor to tracking performance (Alvarez & Franconeri, 2007; Franconeri et al.,

2008; Shim et al., 2008; Tombu & Seiffert, 2008), it may be a good starting place for investigating the intricacies of when gaze is shifted to targets. Another possibility is that the summary statistics of all the dots in a tracking display may have an influence on CTC-viewing. People have been shown to have a surprisingly accurate representation of the center of mass of the group of distractors to which they are not attending (Alvarez & Oliva, 2008). It may be that the distribution of the distractor dots outside the foci of attention can have some influence on either when targets are viewed or when gaze veers off of the center to an undefined location. Additionally, though the CTC-viewing strategy has been shown to not rely directly on a process of minimizing target eccentricities (Fehd & Seiffert, 2008), eccentricity may still play a role in determining gaze during tracking. It is possible that target-viewing is adjusted according to a gaze-optimization process that incorporates the eccentricity of targets, their proximities to distractors, and the overall distribution of objects into the computation. The effects of eccentricity, proximity and distribution are unexplored factors that may account for additional aspects of the CTC-viewing strategy.

One last point to emphasize about what has been learned concerning both CTC-viewing and target-viewing is that they do not work in opposition. An initial idea was that CTC-viewing may be the default eye movement pattern people engage in when looking at targets is too difficult. Yet, the difficulty of looking at targets did not always alter the amount of CTC-viewing. This result suggests that the viewing of targets and the center do not occur in a push-pull manner, where a decrease in one necessarily causes an increase in the other. As addressed in this section, the CTC-viewing strategy has been created to incorporate alternations of gaze between the center and targets. In order to

paint a fuller picture of the CTC-viewing strategy, the factors determining when gaze is shifted between the center and targets must be revealed.

Strategies for Everyday Life

Stepping back from this specific investigation, CTC-viewing is an example of visual selection's response to dealing with a demanding situation. It is not possible to look everywhere you want to attend to at once, thus people often deal with this conundrum by settling their gaze in the middle of the action and moving it to inspect a specific object only when necessary. Moving our eyes strategically during tracking is not an isolated instance of attempting to increase the efficiency of a task when resources are limited. In an analogous way, hospital physicians that are responsible for the health of several people will assign staff to monitor the vital signs of patients on their rounds but will treat them directly if an emergency arises. The key component for both CTC-viewing and administering health care seems to be to strive for the best result while working within the current limitations by using both overt and covert mechanisms to get the job done. It is through these sorts of combinations of overt and covert methods that our processing powers and productivity can reach the high levels that we do. As our society reaches higher and higher levels of complexity with advances in technology and increases in population, it will be more important to understand what strategies for coordinating our efforts and actions are most beneficial to interacting with the world around us.

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